

TECHNICAL REPORT

TREATMENT OF CYANIDE HEAP LEACHES AND TAILINGS

September 1994

U.S. Environmental Protection Agency
Office of Solid Waste
Special Waste Branch
401 M Street, SW
Washington, DC 20460



DISCLAIMER AND ACKNOWLEDGEMENTS

This document was prepared by the U.S. Environmental Protection Agency (EPA). The mention of company or product names is not to be considered an endorsement by the U.S. Government or the EPA.

This Technical Resource Document consists of two sections. The first section is EPA's Profile of the lead-zinc industry; the remaining section is a Site Visit Report from a site visit conducted by EPA. The Technical Report was distributed for review to the U.S. Department of the Interior's Bureau of Mines and Bureau of Land Management, the U.S. Department of Agriculture's Forest Service, the Western Governors Association, the Interstate Mining Compact Commission, and the American Mining Congress. EPA is grateful to all individuals who took the time to review sections of this Technical Report Document.

The use of the terms "extraction," "beneficiation," and mineral processing" in this document is not intended to classify any waste streams for the purposes of regulatory interpretation or application. Rather, these terms are used in the context of common industry terminology.

TABLE OF CONTENTS

	<u>Page</u>
TREATMENT OF CYANIDE HEAP LEACHES AND TAILINGS	1
1. INTRODUCTION	1
2. CYANIDE LEACHING	1
2.1 Heap Leaching	1
2.2 Tank Operations (Carbon-in-Pulp and Carbon-in-Leach)	3
3. CYANIDE TREATMENT TECHNOLOGY	4
3.1 Rinsing of Heaps	4
3.2 Sulfur Processes	5
3.3 INCO Process	7
3.4 Noranda Process	8
3.5 Alkaline Chlorination Process	9
3.6 Hydrogen Peroxide Process	10
3.7 AVR Cyanide Recovery Process	12
3.8 Biological Treatment	14
3.8.1 Introduction	14
3.9 Homestake Mine, South Dakota	15
3.10 Pintail's Biotreatment Process	16
3.11 Natural Degradation	16
4. OTHER RELATED ISSUES	18
4.1 Closure and Reclamation Issues	18
4.1.1 Analytical Methods	18
4.1.2 Mobility of Constituents In Heaps and Impoundments	19
4.1.3 Reduction of Constituents in Solutions	21
4.1.4 Rinsing/Treatment Duration	22
4.1.5 Water Balance	22
4.1.6 Percolation of Solution through Heaps	23
4.1.7 Acid Generation	23
5. REGULATORY PROGRAMS	23
5.1 Federal Requirements	23
5.1.1 Environmental Protection Agency - NPDES Program	23
5.1.2 Bureau of Land Management	24
5.1.3 U.S. Forest Service	26
5.1.4 National Park Service	27
5.2 State Requirements	27
5.2.1 California	27
5.2.2 Colorado	31
5.2.3 Idaho	32
5.2.4 Montana	33
5.2.5 Nevada	34
5.2.6 South Carolina	35
5.2.7 South Dakota	36
6. CASE STUDIES	37
6.1 Hecla, Yellow Pine, Idaho	38
6.2 Zortman Mining, Landusky Heaps, Montana	38
6.2.1 McCoy/Cove Mine, Echo Bay Mining Company, Nevada - INCO process	39
7. REFERENCES	41

LIST OF TABLES

	<u>Page</u>
Table 1. Relative Stabilities of Cyanide Complexes in Water	20
Table 2. Some Metal-Cyano-Complex Ions and Their Stability Constants	20
Table 3. Summary of State Requirements: Cyanide Heap Leach and Tailings Impoundment Closure and Reclamation	28

LIST OF FIGURES

	<u>Page</u>
Figure 1. INCO Sulfur Dioxide-Air Process	6
Figure 2. Alkaline Chlorination Process	9
Figure 3. Hydrogen Peroxide Process	11
Figure 4. AVR Cyanide Recovery Process	13
Figure 5. Biological Treatment Process	18

TREATMENT OF CYANIDE HEAP LEACHES AND TAILINGS

1. INTRODUCTION

The purpose of this report is to provide information on cyanide treatment methods for heap leaches and tailings activities associated with cyanidation operations, including disposal units that receive wastes from such operations. Such practices not only prevent environmental degradation but also prevent costly remedial actions under Superfund and other programs. The Agency has collected this information for use in regulatory agencies and the mining industry to better understand treatment options. The Agency has not, however, evaluated the efficiency of the methods discussed.

Cyanidation includes both heap leaching and tank leaching. Spent ore or tailings containing residual amounts of cyanide are generated as wastes. These wastes are typically treated to neutralize or destroy cyanide prior to final closure. This report discusses cyanide detoxification or treatment in terms of chemistry, duration, removal efficiencies, and advantages and limitations. After a discussion of treatment techniques, the report describes typical closure and reclamation activities for heaps and tailings impoundments, identifying issues that are still outstanding.

The report also describes Federal and state requirements that apply to cyanide operations. In addition, selected case studies at active mines are presented. The active sites were selected to reflect a range of facility types, a large heap operation with several permanent pads, and a site using biological treatment by bacteria.

The report is based on literature reviews, publicly available documents, and telephone contacts with Federal and state agencies.

2. CYANIDE LEACHING

Cyanidation uses solutions of sodium or potassium cyanide as lixiviants (leaching agents) to extract precious metals from ore. Cyanidation techniques used in the gold industry today include heap or valley fill leaching, agitation leaching followed by carbon-in-pulp (CIP), and agitated carbon-in-leach (CIL). Cyanidation is best suited to fine-grain gold in disseminated deposits. Heap or valley fill leaching is generally used to beneficiate ores containing less than 0.04 Troy ounces/ton (oz/t). CIP and CIL techniques, commonly referred to as tank or vat methods, are generally used to beneficiate ores containing more than 0.04 oz/t. These cut-off values are dependent on many factors, including the price of gold and an operation's ability to recover the precious metal (van Zyl et al. 1988). For the purposes of this report, a brief description of both heap and tank leaching is provided below. A more detailed description may be found in EPA's Technical Resource Document: Extraction and Beneficiation of Ores and Minerals Volume 2: Gold (EPA 1992a, 1994), which can be obtained from the National Technical Information System or at EPA Regional Libraries.

2.1 Heap Leaching

Since the 1970's and early 1980's, heap leaching has developed into an efficient way to beneficiate a variety of low-grade, oxidized gold ores. Compared to tank leaching, heap leaching has several advantages, including simplicity of design, lower capital and operating costs, and shorter startup times. In many cases, heaps are constructed on lined pads with ore sent directly from the mine (run-of-mine ore) with little or no preparation. However, at about half of the heap leaching operations, ore is crushed and agglomerated prior to placement on the heap to increase permeability of the heap and maintain the high pH needed for leaching to occur (Bureau of Mines 1986). Agglomeration entails mixing the crushed ore with portland cement, lime, ash, or other materials. In some cases, after crushing, sulfide ores may be treated by roasting, autoclaving, bio-oxidation, or chlorination prior to heap leaching.

Two common types of pads used in gold heap leaching include permanent heap construction on a pad from which the leached ore is not removed and on-off pads, which allow the spent ore to be removed following the leach cycle and fresh ore to be placed on the pad. Permanent heaps are typically built in lifts. Each lift is composed of a 5- to 30-foot layer of ore. On-off pads are not commonly used in the industry and are constructed to allow spent ore to be removed after the leaching cycle and re-use of the pad (Lopes and Johnston 1988).

The reaction of the cyanide solution with the free gold is oxygen-dependent. Therefore, the solution is oxygenated prior to application or during spraying. The solution concentration is generally between 0.5 and 1.0 pounds of sodium cyanide per ton of solution. Cyanide solution is applied using drip or spray irrigation. The cyanide leachate percolates through the ore and is collected by pipes located under the pile or carried on the asphalt or plastic liner directly to ditches around the pile (Bureau of Mines 1986; Lopes and Johnston 1988). The pregnant solution is then collected in a lined pond or tank. (Bureau of Mines 1984).

Leaching occurs according to the following reactions, with most of the gold dissolving in the second reaction (van Zyl et al. 1988):

- $4\text{Au} + 8\text{NaCN} + \text{O}_2 + 2\text{H}_2\text{O} \rightarrow 4\text{NaAu}(\text{CN})_2 + 4\text{NaOH}$ (Elsener's Equation and Adamson's 1st Equation)
- $2\text{Au} + 4\text{NaCN} + \text{O}_2 + 2\text{H}_2\text{O} \rightarrow 2\text{NaAu}(\text{CN})_2 + \text{H}_2\text{O}_2 + 2\text{NaOH}$ (Adamson's 2nd Equation)

Leaching is generally effective at a pH of 9.5 to 11, with the optimum being approximately 10.5. More acidic conditions may result in the loss of cyanide through hydrolysis, reaction with carbon dioxide, or reaction with hydrogen to form hydrogen cyanide (HCN). Alternatively, more basic conditions tend to slow the reaction process (Bureau of Mines 1984). Typically, the recovered cyanide solution, the pregnant solution, contains between 1 and 3 ppm of gold material (Bureau of Mines 1986). Irrigation of the heap generally stops when the pregnant solution falls below about 0.005 ounces of gold per ton of solution (Lopes and Johnston 1988). Recovery rates for heap and valley fill leaching range from 60 to 80 percent. Leaching typically takes from several weeks to months, depending on the permeability and size of the pile. An "average/normal" leach cycle takes approximately three months (Lopes and Johnston 1988).

After leaching has been completed, such that no further recovery of gold will occur, the spent ore and remaining cyanide solution become wastes. There are several approaches to the decommissioning of cyanide-contaminated ore heaps and neutralizing of cyanide solutions. Typically, the heap is rinsed with water until the cyanide concentration in the effluent is below a specific standard set by the State regulatory agency. In some cases, analysis of the heap solids is required. The heap may then be reclaimed with wastes in place. If the heap is an on/off pad, the spent ore will have been periodically removed to a permanent disposal area. Solution ponds and other areas are also neutralized and closed, sometimes with residue or wastes in place, prior to reclamation. Cyanide treatment technologies are discussed in detail in Section 3. Closure and reclamation are discussed in detail in Section 4. State regulations and their applicability to closure and reclamation is discussed in Section 5.

2.2 Tank Operations (Carbon-in-Pulp and Carbon-in-Leach)

In Carbon-in-Pulp and Carbon-in-Leach cyanidation methods, primary leaching takes place in a series of tanks. Finely ground gold ore is slurried with the leaching solution. The resulting gold-cyanide complex is then adsorbed on activated carbon. CIP conducts the leaching and recovery operations in two separate series of tanks, while CIL conducts them in a single series. Tank operations have significantly higher recovery efficiencies than heap leaching facilities, recovering from 85 to 98 percent of the gold contained in the ore. Generally, CIP or CIL methods are used for high grade ore.

Oxide ores are typically beneficiated by grinding to 65 mesh and leaching with 0.05 percent sodium cyanide over a 4- to 24-hour period with a pulp density of 50 percent solids. Sulfide ores are typically beneficiated by grinding to 325 mesh and leaching with 0.1 percent sodium cyanide for a 10- to 72-hour period with a pulp density of 40 percent solids. (Weiss 1985).

In the CIP method, a slurry consisting of ore, water, cyanide, and lime is pumped to the first series of tanks for agitation and leaching. Gold is leached from the ore in the leach tank train. The slurry containing leached ore and pregnant solution is pumped to the second series of tanks for gold recovery. In the second series of CIP tanks, the slurry is introduced into a countercurrent flow with activated carbon. The slurry enters the first tank in the series containing carbon that is partially loaded with the gold-cyanide complex. In the suspended slurry, the activated carbon adsorbs gold material on the available exchange sites. As the carbon material becomes laden with precious metals, it is pumped forward in the circuit towards the incoming solids and pregnant solution. Thus, in the last tank, the low-gold percentage solution is exposed to newly activated and relatively gold-free carbon that is capable of removing almost all of the remaining precious metals in the solution. Fully loaded carbon is removed at the feed end of the absorption tank train for further beneficiation. Tailings are discharged to a tailings impoundment. (Bureau of Mines 1978, 1986; Stanford 1987).

The CIL technique differs from CIP in that leaching and recovery of values occur in the same series of tanks. Activated carbon is mixed with the ore pulp in the agitated leach tanks. A countercurrent flow is maintained between the pulp (ore and leaching solution) and the activated carbon. In the first tanks of the series, leaching of the fresh pulp is the primary activity. In later tanks, adsorption onto activated carbon is dominant as the

concentration of gold in solution increases and fresh carbon is added to the system. The loaded carbon is transferred to a stripping vessel while the spent ore is pumped as a slurry to the tailings impoundment (Bureau of Mines 1986; Calgon Carbon Corporation, undated; Stanford 1987). Tailings from tank leaching may be treated prior to discharge to the tailings impoundment. Treatment standards for tailings prior to discharge to the impoundment are often set by the State regulatory authority. As the tailings impoundment becomes dewatered, reclamation may take place.

3. CYANIDE TREATMENT TECHNOLOGY

This section discusses various treatment methods for neutralizing or detoxifying cyanide solutions, spent leached ores, and tailings. Treatment methods range from rinsing heaps with water to more complex techniques such as alkaline chlorination and sulfur dioxide processes, which treat both solutions (spent cyanide solutions and heap rinsate) and slurries (tailings), to recovery of cyanides. Natural degradation and biological treatment of cyanide is also discussed. Where possible, information on chemistry, duration, removal efficiencies, and advantages and limitations has been described, as presented in current literature. Independent field testing or confirmation of these techniques has not been conducted by EPA.

3.1 Rinsing of Heaps

There are three fundamental approaches to the decommissioning of cyanide-contaminated ore heaps. The first is to leave the heap alone and allow the cyanide to degrade, perhaps slowly, but without any human intervention. The second is to dismantle the heap and treat the ore in smaller batches. This approach may be necessary when sections of the heap have become impermeable or when it is desired to reclaim the leach pad area for other uses. The third approach is to rinse the heap to flush out cyanide, with the rinse solution then being treated by any of the methods described below.

Ore heaps may be rinsed with fresh water or with recycled rinse water that has been treated so that it contains little cyanide. The rinse medium may or may not contain chemicals designed to oxidize the residual cyanide as it trickles through the heap.

Mines using cyanide heap leaching will already have equipment available to supply rinse solution. The same system used to apply the cyanide solution can be used for rinsing of the heap. At Echo Bay's Borealis Mine in Nevada, the heaps were rinsed at a rate of about 0.005 gals/min/ft² (Schafer and Associates 1991b) using Rainbird sprinklers. At Brohm Mining's Gilt Edge on-off heap leach operation in South Dakota, a cyanide neutralization solution containing hydrogen peroxide has been applied at a rate of 0.0043 gal/min/ft² (Damon, Smith, and Mudder 1992).

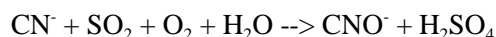
Rinsing also may be accomplished, or enhanced, by natural precipitation; some facilities have included precipitation as part of their detoxification plans (WGA 1991b). However, many cyanide heap leach operations are located in arid areas of the western United States where precipitation rates wouldn't be sufficient to be a source of rinse water.

The duration of rinsing required to reach a specified cyanide level in water leaving the base of the heap may vary considerably. At the Borealis mine, rinsing continued for several months, with each section of the pad being rinsed for 10-20 days. At the Gold Fields Operating Company's Mesquite mine, the heaps were rinsed for five days. At the Snow Caps mine in California, rinsing continued for a total of 160 days, with the effluent from the heap being treated to remove cyanide and then returned to the sprinklers.

The amount of cyanide remaining in the heap and in effluent from it at the end of rinsing program will depend on the hydraulic behavior of the heap as well as on its chemistry. At the Gold Maple mine in Montana, for example, it was found that a heap which had been rinsed with calcium hypochlorite during State-managed remediation activities contained a number of zones with high levels of residual cyanide. Schafer & Associates (1991) believe that this poor rinsing performance was partly due to the same hydraulic problems which had resulted in poor gold leaching efficiency and had made the mine uneconomic.

3.2 Sulfur Processes

In the sulfur processes, cyanide in solution is oxidized to cyanate using sulfur dioxide or ferrous sulfate and air in the presence of copper ion:



The sulfuric acid formed in the reaction is neutralized with lime. Cyanate may be less toxic than cyanide to fish, animals, and humans. Higgs and Associates (1992) report that CNO^- is 3,000 - 5,000 times less toxic than CN^- . The International Nickel Company's (INCO) SO_2 -air process is one of two patented sulfur dioxide treatment processes. The other is patented by Noranda Inc. The INCO process can be applied both to barren solutions and to cyanide-bearing tailings. Reagent requirements may be higher for tailings. The Noranda Process has been used for wastewater solutions, but may be applicable to heaps.

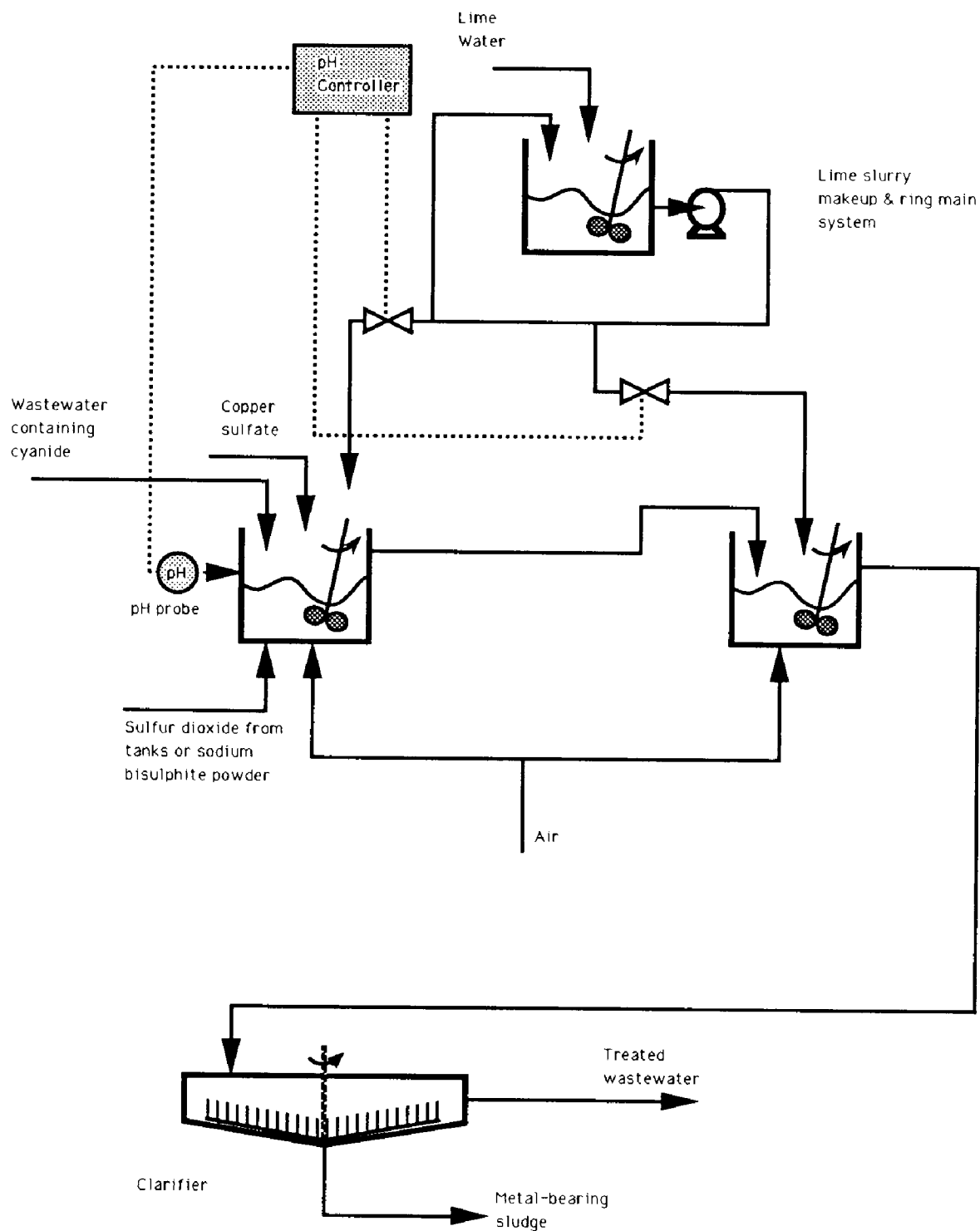


Figure 1. INCO Sulfur Dioxide-Air Process

(Source: Adapted from Higgs 1992)

3.3 INCO Process

Equipment requirements for the SO_2 process are relatively simple. Wastewater to be treated is introduced into a mixing vessel, where it is reacted with sulfur dioxide or sodium bisulfite (Figure 1). The theoretical SO_2 requirement is 2.64 lb/lb CN. INCO has reported actual dosages to be 3 - 5 lb/lb for clear barren solutions and 4 - 7 lb/lb for tailings slurries. Air is sparged into the vessel. Copper sulfate is added as a catalyst at a concentration of approximately 50 mg/l. The pH is controlled by addition of lime. The optimal pH range is 8-10. While it is possible to feed the lime as a powder, dry feeding equipment is troublesome and not suited to processes such as this which have short residence times. A more reliable solution is to make up a slurry of lime and recirculate it through a ring main. Electronically or pneumatically controlled valves can be opened to obtain long or short pulses of well-mixed slurry. Similar lime dosing circuits are used in many ore flotation mills.

INCO tests showed that a feed stream could be reduced from 1680 mg/l CN_T^- to 0.13 mg/l CN_T^- using a retention time of 97 minutes in a one-stage reactor. A feed containing 420 mg/l CN_T^- was treated to 0.11 mg/l CN_T^- using two reactors in series with a retention time of 26 minutes in each. These tests were conducted in a continuous flow apparatus (Ingles and Scott 1987). Total cyanide can be reduced to 0.5 mg/l or less in low nickel wastewaters. About 1 mg/l is achievable in high nickel wastewaters (Smith and Mudder 1991). Other data from bench-scale tests indicate that $\text{CN}_T^- < 0.1$ mg/l is achievable.

An INCO SO_2 -air treatment process was installed at Echo Bay's Cove-McCoy mine in Nevada in 1990. This system is designed to treat tailings pulp (Devuyst 1992). The pulp is 40 wt percent solids and the flow rate of cyanide to the treatment process is 270 kg CN^- per hour. The authors do not give a feed concentration, but at a total mill throughput of 8,500 short tons/day this would correspond to a total cyanide concentration of about 335 mg/l. The addition rate of SO_2 is adjusted based on periodic analyses of the feed stream (feed-forward or anticipatory control). Fine adjustment is provided by a feed-back or reactive control loop based on measurements of CN^- and pH in the reactors and in the effluent. This system was designed to be capable of reaching 5 mg/l CN_{WAD} , if necessary.

The INCO process has also been applied to the detoxification of a heap leach pad at the Snow Caps mine in California (Vergunst 1991). The existing barren pond was converted for use as a reactor by adding an air sparging system. Sodium metabisulfite was used as the SO_2 source. The pH was controlled by addition of NaOH rather than lime; manual control of pH was found to be satisfactory. The system was operated under total recycle, with all of the reactor effluent being returned to the top of the leach pad, until total cyanide reached acceptable levels. After 130 days of operation, the total cyanide level in the effluent was < 0.2 mg/l. Fresh water was then used to rinse the heap for an additional 30 days, after which the heap and spent solution ponds were deemed to have met State requirements for reclassification as "Group C" waste. This project was carried out using existing mine equipment, a secondhand blower and some piping. Total costs to the mine operator were under \$ 125,000. A pre-construction estimate had indicated that merely doing nothing and allowing the cyanide to degrade naturally to the levels specified by the State would have taken three years and cost \$ 1,500,000 for security and maintenance.

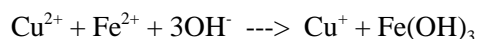
Limitations to the SO₂ process appear to be that the reaction proceeds more slowly at low temperatures. A drop in temperature from 25 °C to 5 °C can cause a tenfold decrease in reaction rate. Correspondingly larger residence times and tank volumes would be required to achieve the same CN⁻ removal efficiencies at lower temperatures. The SO₂ process generally does not remove thiocyanate, cyanate, or ammonia. Cyanate can be transformed into ammonia by microbial action; ammonia is toxic to fish. In addition, removal of toxic metals may not be sufficient to meet permit requirements.

3.4 Noranda Process

Noranda, Inc. holds a patent for detoxification of cyanide in tailings effluent (US patent 4840735; Canadian patent 1321429). The process was tested and is still in use at Noranda's Hemlo Gold Mines, Inc. Golden Giant site in Northwestern Ontario, Canada. Although similar to the INCO process, the Noranda Process was developed for the specific site and is well suited to ores with significant antimony or arsenic concentrations. A representative of Noranda stated that if the cyanide mine effluents were primarily cyanide and cyanide metals, and did not contain arsenic or antimony, then the Noranda Process would likely be less economical than other existing methods of cyanide detoxification. While the Noranda Process has been used to treat cyanide effluents, it may be adaptable to heap detoxification. (Noranda 1994, Konigsmann et al 1989)

In the initial Hemlo tests, liquid sulfur dioxide and copper sulfate were added to the cyanide-containing solution to destroy the cyanide, with a typical ratio of sulfur dioxide to total cyanide in the feed solution of 7 to 1 (weight basis). Total cyanide concentrations were reduced from 47 mg/L to 0.15. Although the results were encouraging, Hemlo had significant safety concerns regarding the storage of the sulfur dioxide, and developed a ferrous sulfate process. (Konigsmann et al 1989)

In the Noranda Process, copper and ferrous sulfate is added to the cyanide effluent, with the following reaction:



In the presence of hydroxide ions, the ferrous ion is oxidized to ferric oxide while the cupric ion is simultaneously reduced to cuprous ions. The cuprous ion removes free cyanide as an insoluble precipitate of cuprous cyanide (Konigsmann et al 1989). The formation of cuprous cyanide creates a shortage of free cyanide ions in solution, which leads to further removal of cyanide through dissociation of soluble metal cyanide complexes of copper, zinc and nickel into simple cyanide and metal ions. Final removal of cyanide is completed by the addition of hydrogen hydroxide at high pH in a second stage to oxide the residual simple cyanides.

Noranda claims the copper requirements are directly related to the amount of cyanide present in the wastewater, and that a 3 to 1 ratio of copper to cyanide is sufficient for effective cyanide removal. At the

Hemlo site, typical operating results reduced the total cyanide concentrations from 23 to 0.13 mg/L. (Konigsmann et al 1989)

3.5 Alkaline Chlorination Process

The alkaline chlorination process is one of the oldest cyanide destruction methods (Higgs 1992). In this process, cyanide in solution is oxidized to cyanate using chlorine or hypochlorite in solution: $\text{CN}^- + \text{Cl}_2 \rightarrow \text{CNCI} + \text{Cl}^-$
 $\text{CNCI} + \text{Cl}^- + 2\text{OH}^- \rightarrow \text{CNO}^- + \text{Cl}^- + \text{H}_2\text{O}$

Alkaline chlorination can be applied to both clear wastewaters and slurries.

Equipment requirements for the alkaline chlorination process are similar to those for the other two oxidation processes (hydrogen peroxide, sulfur dioxide). Wastewater to be treated is introduced into a mixing vessel, where it is reacted with chlorine or hypochlorite (Figure 2). The pH is maintained in the alkaline range by addition of lime. Precipitated metals are removed in a clarifier before the wastewater is discharged.

Smith and Mudder (1991) state that the first-stage reaction (cyanide to cyanate) requires approximately 15 minutes at pH 10.5. Hydrolysis of the cyanate to ammonia and carbonate requires an additional 1-2 hours.

The Giant Yellowknife mine reported that the process reduced CN_T^- from 7.8 mg/l to 0.05 mg/l. Fifteen days retention in a polishing pond reduced CN_T^- to 0.02 mg/l. These data were averages for the 1984 operating year. At the Mosquito Creek mine, total cyanide was reduced from 310 mg/l to 25 mg/l and WAD cyanide was reduced from 226 mg/l to 0.5 mg/l.

Few sites are currently using this technology. The Thunder Mountain Mine in Idaho operated from 1984 to 1991 (Mohr Undated). The mine was operated as an on-off heap leach. Leached ore was treated by alkaline chlorination. This method was also used to treat wastewater generated by rinsing of the pads during decommissioning. Effluent from the treatment process was disposed at a "wastewater land application facility", so that there was no direct NPDES point source discharge. However, the operator may be required to apply for a NPDES permit to cover storm water discharges from the site under recently EPA promulgated regulations. Mohr (Undated) does not give any details regarding cyanide destruction efficiency or operating parameters.

Generally, wastewaters which can be discharged indirectly through natural or artificial wetlands or land treatment facilities do not need to meet the same requirements as direct discharges, because natural processes in the wetland lead to additional cyanide destruction and metals removal.

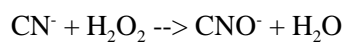
Environment Canada conducted a study of this process at three mills in British Columbia and one in the Northwest Territories during the period 1981 - 1983. The Giant Yellowknife mine used this process followed by an arsenic precipitation step and a polishing lagoon to treat a wastewater which

had relatively low CN_T^- values. Reagent costs were very high, about CAN\$ 46.50 per kg CN_T^- in 1983. This would correspond to approximately US\$ 43.50 at 1992 prices. This was partly due to the additional chlorine loading required to make the arsenic precipitation step operate properly, and partly due to the very remote location of the mine, which resulted in high transportation costs.

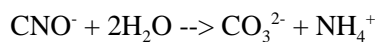
Limitations of this process are that it does not remove iron cyanides, and chloramines and free chlorine remain in solution; these are toxic to fish.

3.6 Hydrogen Peroxide Process

In the hydrogen peroxide process, cyanide in solution is oxidized to cyanate using hydrogen peroxide in the presence of copper ion:



Cyanate ion hydrolyses to form ammonia and carbonate:



This process can be applied to wastewaters. Reagent requirements increase when this method is applied to slurries.

Equipment requirements for the hydrogen peroxide process are similar to those for the INCO process. Wastewater to be treated is introduced into a mixing vessel, where it is reacted with hydrogen peroxide (Figure 3). Copper sulfate is added as a catalyst. The pH is controlled by addition of lime. Hydrogen

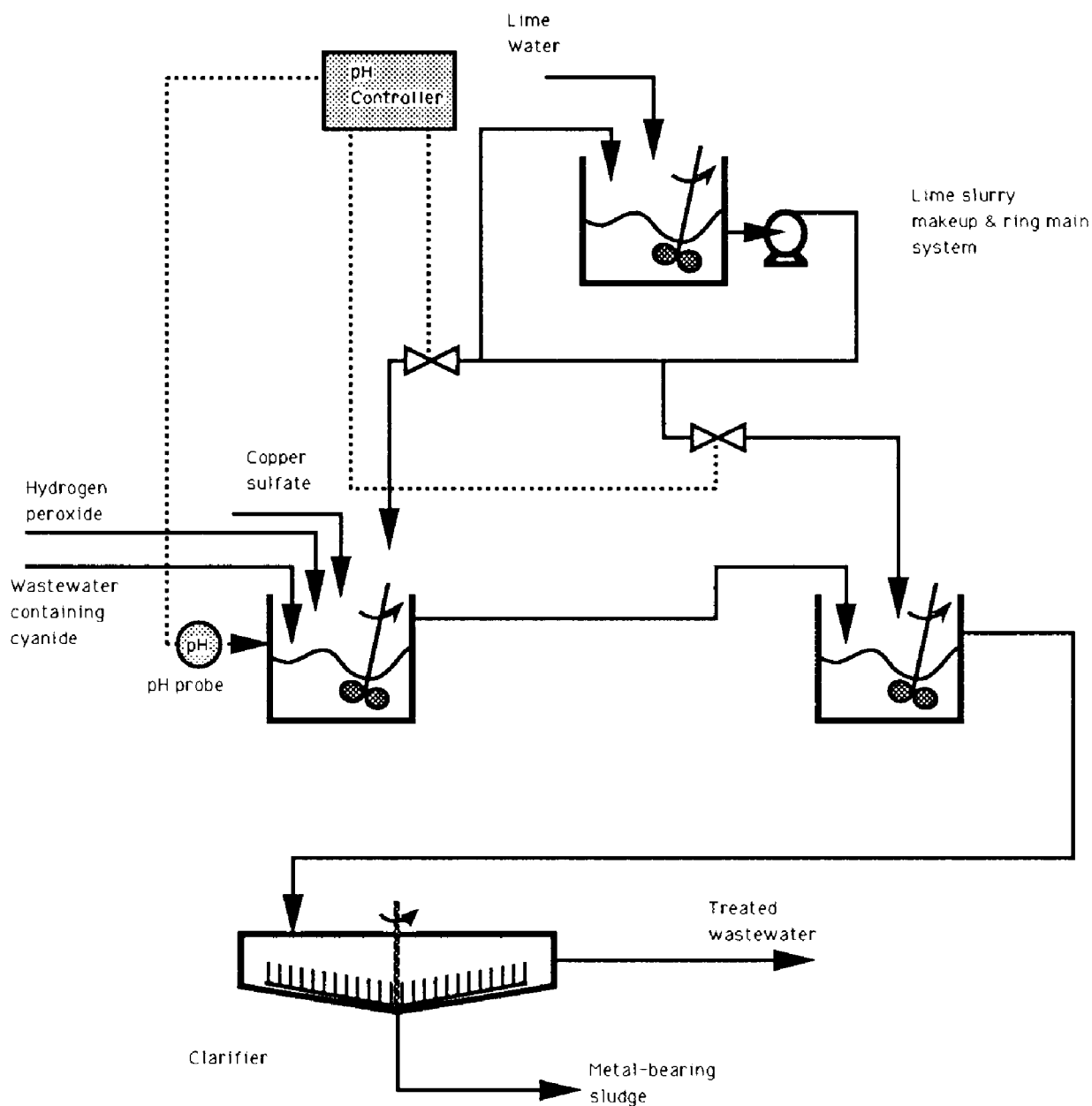


Figure 3. Hydrogen Peroxide Process

(Source: Adapted from Higgs 1992)

peroxide is a strong oxidizer, which can give rise to violent explosions and fires if brought in contact with combustible organic material (wood, old cloth rags). Specially designed storage tanks and handling equipment must be used.

Griffiths (Degussa 1988) reported that a mine in northern Ontario, Canada was planning to use this process. Under these cold conditions, batch tests indicated that 27 hours would be required to reduce total cyanide from 25.7 mg/l to 0.94 mg/l. Higgs (1992) indicates that retention times should be in the range of 45 minutes to 2 hours, but bench scale tests are needed for each individual waste stream.

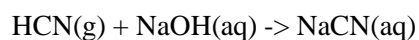
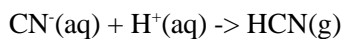
An example of removal efficiencies is provided by the Annie Creek Mine (McGrew and Thrall, cited in Brooks 1992). At this mine, effluent from a heap was reduced to 0.57 mg/l CN_T^- and 0.09 mg/l CN_{WAD}^- after 97 days of rinsing with H_2O_2 solution.

The hydrogen peroxide process was applied at the Timberline mine in Utah (Brooks 1992). This gold mine operated as a heap leach operation from 1984-1986. In 1989, the operator declared bankruptcy and forfeited the bond to Tooele County. The sheriff's department arranged for the placing of 800 pounds of calcium hypochlorite in the solution pond, but this was found not to be sufficient to neutralize the cyanide leached from the pile, especially after heavy rainfall events. The county, the State, and the U.S. Bureau of Land Management decided to treat the leached ore in lifts consisting of layers one foot thick, using 0.01 gallons of H_2O_2 per ton of ore. After treatment, the ore averaged 6.3 mg/kg CN_{WAD}^- and 24 mg/kg CN_T^- . By 1991, the cyanide levels were 2.12 mg/kg CN_{WAD}^- and 8.46 mg/kg CN_T^- in the leached ore, and 1.11 mg/l CN^- in rinsate samples. The state considers the heap to be neutralized. This project was completed on a very low budget (the \$ 20,000 bond) using BLM personnel and equipment and volunteers from a nearby mining company.

The limitations of hydrogen peroxide treatment include handling and costs. In particular, hydrogen peroxide is a hazardous material, and can be expensive. Special equipment for hydrogen peroxide service may increase the total capital cost. The treatment process generates ammonia, which is toxic to fish.

3.7 AVR Cyanide Recovery Process

In the handling of cyanide solutions, significant efforts are taken to ensure that the pH is always kept in the alkaline range so that toxic hydrogen cyanide gas will not be released. The Acidification-Volatilization-Recovery (AVR) process runs directly counter to this principle. The pH of a cyanide solution is lowered by addition of sulfuric acid so that HCN gas is formed. This gas can then be absorbed into a NaOH solution:



The process has generally been applied to barren solutions. However, a system to handle slurries was designed for the Golden Cross mine in New Zealand (Smith and Mudder 1991).

The Acidification-Volatilization-Neutralization Process for cyanide recovery is illustrated in Figure 4. In this process, wastewater containing cyanide is mixed with sulfuric acid, liberating HCN gas. The mixing vessel must be sealed. The liquid stream leaving the reactor is stripped with a current of air in a packed column. The HCN-laden air is absorbed in a second column containing a downward-flowing stream of caustic soda, forming sodium cyanide. This can be returned to the leaching process. Lime is added to the detoxified

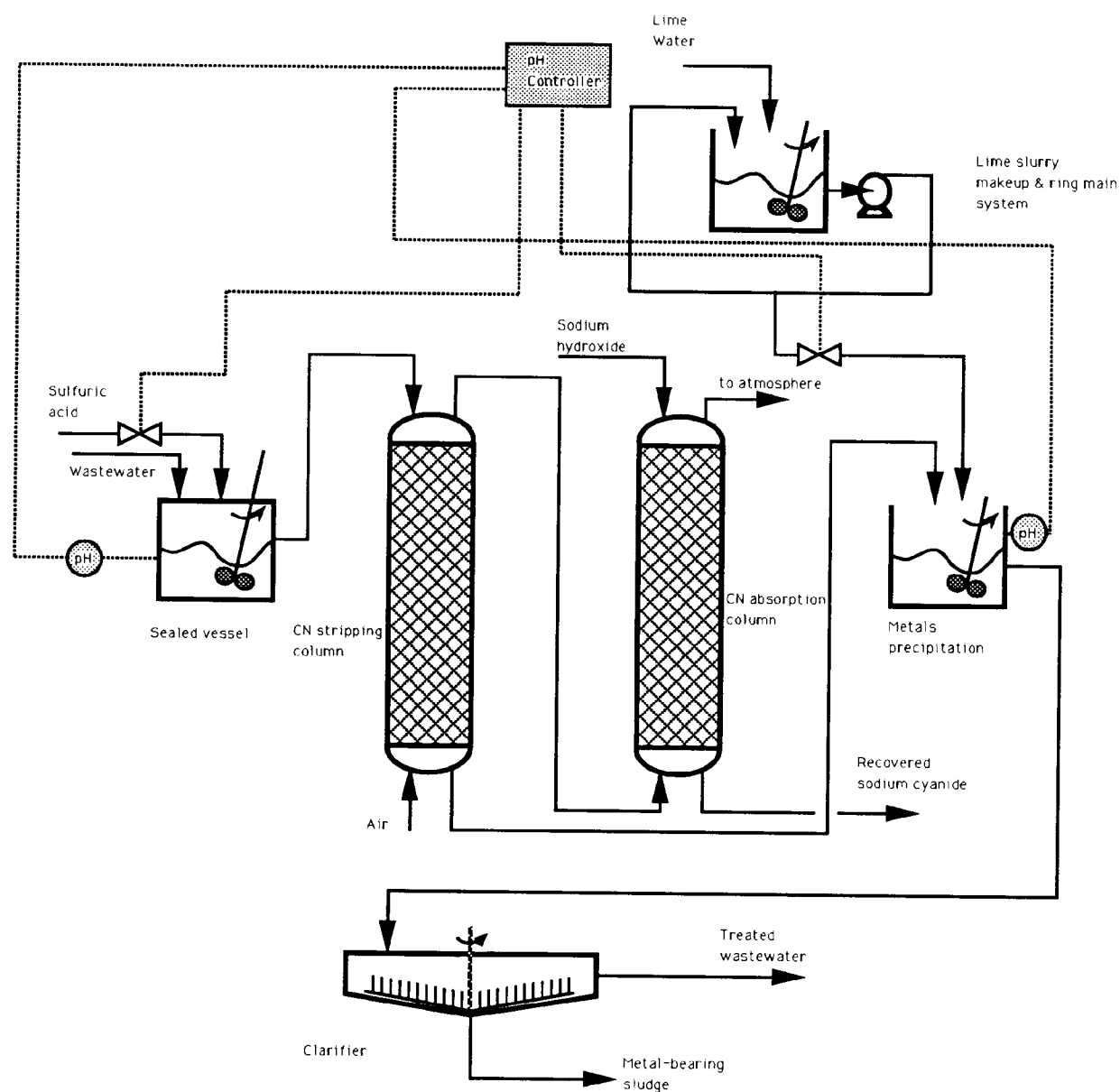


Figure 4. AVR Cyanide Recovery Process

(Source: Adapted from Higgs)

wastewater to precipitate heavy metals. Based on bench-scale tests, total cyanide levels were routinely reduced from 330 mg/l to < 2 mg/l. (Smith and Mudder 1991). No examples could be found in the literature of an application of this technology in the United States.

An early version of this technology was operated by Hudson Bay Mining and Smelting, Flin Flon, Manitoba from 1931-1978. Four stripping towers were used in series. The cyanide content was lowered from 560 mg/l to 44 mg/l and the resulting effluent, which contained copper cyanide, was fed to a copper sulfate plant. As an example of duration, the process as applied at Flin Flon, Manitoba, had a liquid flowrate in the cyanide stripping column of 107 m³/hr and an air flowrate about 525 times greater. This process was also being used in 1984 at a silver mine in Mexico. A more modern version of the process was operated from 1985-1987 at the Beaconsfield gold mine in Tasmania. The system was designed for maximum safety, incorporating an enclosed negative pressure system. Cyanide recoveries of nearly 95 percent were reported. (Smith and Mudder 1991)

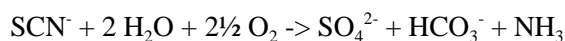
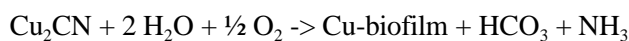
One of the advantages of this technology over the treatment alternative is that cyanide can be recovered for reuse. The economics may be favorable in very remote locations where the costs of cyanide threaten the economics of the mining project. In addition, the potential aquatic toxicity of cyanide oxidation products (cyanate, ammonia, chloramines) does not arise.

The major limitation of this technology is that it is a more complex process than the various treatment alternatives. Sealed mixing vessels and packed columns are required. All mining operations involving cyanide are operated under alkaline conditions to avoid the evolution of HCN. This process may be perceived as too hazardous because HCN is deliberately generated. It also has not been conclusively demonstrated that this technology can achieve allowable discharge limits for CN_T⁻ in this country. The economics may vary depending on the value of the recovered cyanide. OSHA, EPA, and insurance requirements associated with the handling of free HCN in the U.S. may increase both capital and operating costs and limit the applicability of cost estimates from other countries. Studies in New Zealand indicated that the AVR process could generate an operating profit of NZ\$ 2.15-3.20 per ton of ore processed. However, cyanide costs in New Zealand are 3-5 times higher than those in the United States.

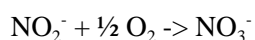
3.8 Biological Treatment

3.8.1 Introduction

Microbial action, either naturally occurring or as a cyanide detoxification technique, causes transformation of cyanide to ammonia. Metal ions released from metal cyanides will be absorbed by the biomass and thiocyanates are converted to sulfate:



Further microbial action will convert the ammonia to nitrate:



The aim of biological treatment processes is to greatly increase the rate at which these natural transformations occur.

Until recently, known applications of this technology were confined to barren solutions. A Homestake Mine has used biological treatment on cyanide wastewaters. In addition to Homestake, biological treatment has been applied at the Hecla Yellow Pine heap in Idaho. Hecla's treatment has reduced cyanide levels to the State detoxification criteria of 0.2 mg/l WAD cyanide (Idaho 1993). Pintail Systems Inc. has recently applied biological treatment to heap leaches at the Hecla Yellow Pine Site.

3.9 Homestake Mine, South Dakota

The Homestake gold mine in South Dakota has also implemented a biological treatment system. A simplified flowsheet of the Homestake plant is shown in Figure 5.

Wastewater to be treated is dosed with phosphoric acid, which acts as a nutrient. The water is then fed to the first set of rotating biological contactors (RBCs). These units consist of a shaft of circular plastic elements revolving partly submerged in a contour-bottomed tank. The disks are spaced such that wastewater can enter between them. When rotated out of the tank, air enters the spaces while the liquid trickles out over films of biological growth attached to the media. The biomass consumes phosphate and other nutrients in solution, and also converts cyanide to ammonia. Excess biomass flows out of the unit with the wastewater. A second set of RBCs is used to convert the ammonia to nitrate. Toxic metals and biomass can be precipitated using ferric chloride and a polymeric agent. A sludge of metals and microbes then settles out in the clarifier, and can be removed for disposal. The effluent is polished using a sand filter before being discharged. (Ingles and Scott 1987; Higgs 1992)

The Homestake mine reduced total cyanide levels from 10 ppm (feed level) to 0.3 ppm cyanide in the effluent.

The US Bureau of Mines conducted a demonstration project to study the viability of bacterial cyanide oxidation at USMX's Green Springs mine in Nevada (Lien and Altringer 1993). Staff at the Bureau's Salt Lake Research Center had isolated a cyanide-degrading bacterium, *Pseudomonas pseudoalcaligenes*, from a tailings pond containing 280 mg/l CN⁻. This bacterium was cultivated at the Research Center and introduced into the carbon adsorption tanks at Green Springs. The tanks, transformed into bioreactors, were used to treat water being recirculated through the ore heaps as part of the closure process. WAD cyanide was reduced from 20 mg/l to 8.5 mg/l over a period of 15 weeks.

With regard to duration, performance of RBCs depends in large part on the loading of Biochemical Oxygen Demand (BOD) per unit area of contactor surface. At the Green Springs mine, residence times in the five carbon tanks were on the order of 80 minutes.

3.10 Pintail's Biotreatment Process

The Pintail System Inc. approach to biotreatment of heap leach pad cyanide solutions uses bacteria native to the project environment. The process involves isolating and enhancing native bacteria with the ability to use or transform cyanide into non-toxic components: carbon dioxide, water and nitrogen. These "working" bacteria are grown to concentrations capable of supporting effective biotreatment, while the "non-working" bacteria are selectively eliminated from the microbial community. Pintail has researched both heterotrophic and autotrophic strains of bacteria for cyanide detoxification. As long as the biotreatment solutions are heated and the solution is effectively applied to the heap, cyanide biotreatment in cold weather is possible (Caldwell, 1993).

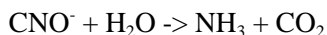
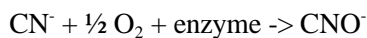
Pintail Systems Inc. conducted a full scale cyanide detoxification project at a heap leach pad at the Hecla Mining Company's Yellow Pine Mine near McCall, Idaho (Pay Dirt, 1992). The Yellow Pine mine, although located at 6,500 ft. above mean sea level, is in a geographic location that experiences extreme weather conditions similar to an alpine location. This cold temperature environment presents hurdles to the use of bacteria, since the bacteria live and flourish under warm temperatures. The subject of the biotreatment was a heap leach pad 114 feet high, containing 1.3 million tons of material and cyanide solutions with an average WAD cyanide concentration of 46.6 ppm. Bacteria used for the treatment were collected at Yellow Pine from the soil and freshwater environments. To take advantage of the most favorable weather conditions, the detoxification project began in March 1992 when 10,000 gallons of treatment bacteria solution were added to the barren solution pond. In this manner, the treatment bacteria solution was applied to the spent ore by drip irrigation. By May 1992, WAD cyanide levels were below 0.2 ppm. The project ended in mid-September of the same year.

Biological treatment does not require the use of toxic or hazardous chemicals, apart from a small volume of phosphoric acid, which can be stored as a dilute solution. Rotating biological contactors were originally developed for treatment of sewage, and are an alternative to the use of the activated-sludge process with fixed aeration basins and two stages of clarification. Their operating characteristics are well understood. Limitations include the fact that it may not be possible to treat wastewaters containing high concentrations of cyanide and the process may be adversely affected by cold temperatures. Capital costs may also be higher than for the oxidation processes. Capital cost of the Homestake installation has been reported to be about \$ 10 million in 1984. In addition, system response to a sudden change in cyanide or nutrient concentration may be sluggish. Canadian sources have voiced concerns that such a process would not work at the low temperatures encountered in many of their mining districts.

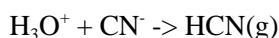
3.11 Natural Degradation

Natural degradation is a general term for all of the processes that may reduce the total cyanide concentration of a waste in the absence of any human intervention. These processes include:

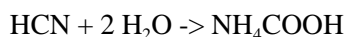
- Microbial generation of cyanate/ammonia in soil:



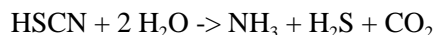
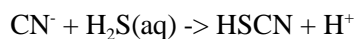
- Volatilization of cyanide from solution after absorption of CO_2 or SO_2 from the atmosphere and consequent formation of acid:



- Hydrolysis in soils:



- Anaerobic biodegradation:



- Complexation:



Natural degradation processes, to some extent, occur in barren solution lagoons, tailings impoundments, and heaps. The efficiency of cyanide destruction may be lower in the interior of heaps or the bottoms of lagoons. No technology is required. Environment Canada found that total cyanide in a tailings pond at Dome Mines, Ontario, decreased from 68.7 mg/l to 0.008 mg/l over a 15-week period from April 30 to August 6, 1980 (Todd 1986). Rates of removal at other sites may be much slower than this.

Echo Bay's Lupin mine uses natural degradation as its sole method of treatment. Tailings are discharged to a series of two surface impoundments with a total retention time of two years. Water from the second impoundment is discharged once a year. Water can then be transferred into this unit from the first impoundment. The mill tailings had an average total cyanide concentration of 166 mg/l in 1991. The effluent from the second impoundment had a total cyanide concentration of 0.019 mg/l. Effluent concentrations ranged from 0.06-0.26 mg/l CN_T^- over the period 1985-1990. (Higgs 1992)

It is unclear, however, if natural processes can generally be used to meet Federal or state standards. One site in Colorado (Battle Mountain Resources, Inc.) planned solely on using natural degradation to reduce cyanide

levels in its tailings slurry, tailings impoundment, and collection pond. Natural degradation, however, was unsuccessful in reducing cyanide to levels required in the permit (4.4 ppm total or 3.8 ppm wad cyanide). In 1991 and 1992, elevated cyanide concentrations (up to 260 ppm total, 240 ppm free and 110 ppm wad) led to a notice of violation and issuance of an administrative order (Colorado Mined Land Reclamation Board 1992).

While natural degradation does not require capital investment or chemical costs, it may never reduce cyanide levels to within the limits specified by state agencies. Information on other constituents was not obtained. It should also be noted that while natural degradation is occurring, the waste may continue to pose a threat to humans and animals. In addition, security costs for preventing public access over a period of several years may prove to be very high.

4. OTHER RELATED ISSUES

4.1 Closure and Reclamation Issues

Cyanide is not the only contaminant that is present in tailings effluents or heaps; numerous other constituents may be present in the waste material and present potential problems. Nitrate and heavy metal migration are examples of other problems that can be faced at closure of cyanide operations. Testing and analysis of cyanide is also an issue because of problems obtaining consistent and reliable test results. Another significant concern is the generation of acid drainage, often caused by the presence of sulfides that break down to form sulfuric acid. Issues relating to metals, acid generation, and operational problems encountered by some facilities are discussed in greater detail below.

4.1.1 Analytical Methods

In developing the national effluent limitation guidelines for the Ore Mining and Dressing Point Source Category (at 40 CFR Part 440), the Agency established a technology-based standard for all discharges from mills that use the "cyanidation" process to recover gold and silver, and mills that use cyanide in froth flotation of copper, lead, zinc, and molybdenum ores. In this process, the Agency considered several methods (e.g., alkaline chlorination, hydrogen peroxide treatment, etc.) used to reduce cyanide levels in mill wastewaters. However, the Agency found that the cyanide levels in both treated and untreated mill wastewaters were below the 0.4 mg/l quantification limit for EPA-approved test methods (i.e., treatment performance could not be evaluated). Therefore, the Agency established a zero discharge requirement as the national technology-based standard. The Development Document for the Part 440 guidelines does indicate that EPA was aware of specific sites where laboratory methods were effectively being used to quantify cyanide removal (but does not describe the methods). The document further suggests these methods could be used by permit writers to establish cyanide limits in individual NPDES permits on a site-by-site basis.

Analytical methods used to determine cyanide concentrations in tailings, heap effluents, and pore water are still being debated. At low concentrations, testing is inaccurate and measurements of cyanide may not be good predictors of actual cyanide concentrations in the field. (Durkin 1990; Colorado 1992a; ORD 1993)

Cyanide is generally measured as one of three forms: free, weak acid dissociable (WAD), and total. Free cyanide refers to the cyanide that is present in solution as CN^- or HCN , and includes cyanide-bonded sodium, potassium, calcium or magnesium. Free cyanide is very difficult to measure. WAD cyanide is the fraction of cyanide that will volatilize to HCN in a weak acid solution at a pH of 4.5. WAD cyanide includes free cyanide, simple cyanide, and weak cyanide complexes of zinc, cadmium, silver, copper, and nickel. Total cyanide measures all of the cyanide present in any form, including iron, cobalt, gold and platinum complexes. (Colorado 1992a)

Many states are continuing to debate over the proper test methods for measuring cyanide (WAD, free, or total). A South Dakota hydrologist with the State Department of Environment and Natural Resources (DENR) points out that many of the commonly used test methods for cyanide leaching yield questionable results for certain parameters. (Durkin 1990)

Mudder & Smith point out that historically, cyanide was regulated as "free" cyanide, but that newer standards specify weak acid dissociable (WAD) cyanide. "Free" cyanide has been shown to be analytically inexact at desired regulatory levels and WAD cyanide levels are more easily determined below one part per million (ppm) and more relevant from an environmental standpoint. (Mudder and Smith 1992)

EPA's Office of Research and Development (ORD) is currently evaluating cyanide test procedures and methods, and is investigating a proprietary, privately developed, distillation method that appears to be successful for cyanide analysis. One of ORD's activities includes revising the current methods for measuring and detecting cyanide fractions and eliminating interferences. ORD is also reviewing performance data and problems of 17 currently used methods. Future efforts of ORD will involve continued evaluation of cyanide species. (ORD 1993)

4.1.2 Mobility of Constituents In Heaps and Impoundments

Because of the great variability among cyanide operations, including ore characteristics and climatic conditions, adequate characterization of wastes and materials is an important consideration for site reclamation. Aqueous cyanide (CN^-) has a negative valence and reacts readily to form more stable compounds. At a pH below 9 (approximately), cyanide forms hydrogen cyanide (HCN), a volatile gas that rapidly evaporates at atmospheric pressure. Aqueous cyanide complexes readily with metals in the ore, forming complexes ranging from readily soluble complexes such as sodium cyanide and calcium cyanide to strong complexes such as iron-cyanide. The stronger complexes are very stable in natural aqueous conditions. Tables 1 and 2 provide the solubility of some of the cyanide complexes. (Colorado 1992a) Limited information was found on the mobility of cyanide and cyanide complexes in closed and/or reclaimed heaps and tailings impoundments. However, at several South Dakota sites, nitrate, one of the degradation

products of cyanide, has been detected in areas beyond the heap. Operators have been able to meet the 0.2 mg/l cyanide detoxification criteria, but elevated levels of nitrate associated with cyanide heap leach on/off operations have prevented facilities from meeting other site-specific state criteria. The nitrate levels in surface runoff from the mine sites have exceeded treatment criteria and low levels of nitrate have been detected in downgradient wells. (Durkin 1990)

In addition, the chemistry of a spent heap or tailings impoundment may change over time. Although effluent samples may meet State requirements, the effluent characteristics may be dependent on the pH. The question of what happens to the heap or impoundment when the pH or moisture content

Table 1. Relative Stabilities of Cyanide Complexes in Water

Cyanide Species	Examples Present in Gold and Silver Processing Solutions
Free Cyanide	CN ⁻ , HCN
Simple Compounds	
Readily Soluble	NaCN, KCN, Ca(CN) ₂ , Hg(CN) ₂
Relatively Insoluble	An(CN) ₂ , CuCN, Ni(CN) ₂ , AgCN
Weak Complexes	Zn(CN) ₄ ²⁻ , Cd(CN) ₃ ³⁻ , Cd(CN) ₄ ²⁻
Moderately Strong Complexes	Cu(CN) ₂ ⁻ , Cu(CN) ₃ ²⁻ , Ni(CN) ₄ ²⁻ , Ag(CN) ₂ ⁻
Strong Complexes	Fe(CN) ₆ ⁴⁻ , Co(CN) ₆ ⁴⁻ , Au(CN) ₂ ⁻
Source: Colorado 1992a.	

Table 2. Some Metal-Cyano-Complex Ions and Their Stability Constants

Metal	Complex Ion	Formula	Stability Constant (at 25° C)
Cobalt (III)	Hexacyanocobaltate	[Co(CN) ₆] ³⁻	1x10 ⁶⁴
Iron (III)	Ferricyanide	[Fe(CN) ₆] ³⁻	1x10 ⁵²
Iron (II)	Ferrocyanide	[Fe(CN) ₆] ⁴⁻	1x10 ⁴⁷
Nickel (II)	Tetracyanonickelate	[Ni(CN) ₄] ²⁻	1x10 ²²
Cadmium (II)	Tetracyanocadmiate	[Cd(CN) ₄] ²⁻	7.1x10 ¹⁶
Manganese (III)	Hexacyanomanganate	[Mn(CN) ₆] ³⁻	5x10 ⁹
Source: Colorado 1992a.			

changes is an important consideration for closure and reclamation. Modeling can be performed to assess the long-term geochemical conditions at the site taking into consideration the chemistry of a spent heap over time, and be used to design closure and reclamation plans. Factors affecting chemical changes in a heap or tailings impoundment include pH, moisture, mobility, and geochemical stability of the material.

4.1.3 Reduction of Constituents in Solutions

According to Mudder and Smith, in addition to high cyanide concentrations, the post-leach solution (pre-cyanide treatment) is likely to have the following characteristics:

- High pH, 9.5 to 11
- Moderate to high dissolved species, mainly sodium, calcium (from added lime), and sulfate
- Potentially elevated metals of ionic-forming complexes such as arsenic, molybdenum, and selenium
- Potentially elevated metals which form soluble metallo-cyanide complexes such as iron, copper, mercury, cadmium, and zinc. (Mudder and Smith 1992)

One site, the Pegasus Gold Relief Canyon mine, used carbon columns to reduce the levels of soluble metals contained in its heap rinse solution. Specific metals, their concentrations and ultimate disposal practices were not obtained. (Logue Undated)

Placer Dome, Inc.'s Campbell gold operation added an arsenic treatment step to its tailings treatment process to remove arsenic from its tailings. Placer Dome uses an autoclave and two neutralization stages to precipitate arsenic and heavy metals. The resulting tailings slurry is then disposed of in a plastic-lined tailings pond. Arsenic concentrations in the tailings slurry have been reduced from around 1.2 mg/l to <0.3 mg/l since the facility added the arsenic treatment as part of its conversion from a roasting system to a pressurized oxidation process for gold recovery. (Mining Engineering 1992)

A representative from Nevada described a problem that occurred with one mine. While recirculating the solution during leaching, gold was removed from the pregnant solution but other metals and constituents continued to accumulate and were not removed from the solution. As a result, during rinsing, the mercury levels in the rinse water were 4.0 mg/l, three magnitudes higher than the primary drinking water standard of 0.002 mg/l. The tremendous amount of water required for consecutive rinses in order to reach the 0.2 mg/l cyanide standards has also been an issue. (Nevada 1993b)

Furthermore, a research study presented at the Environmental Management for the 1990s symposium noted that a several mines in five western states have experienced elevated selenium levels (Altringer 1991). The US Bureau of Mines is investigating the use of biological and chemical reduction of selenium in cyanide tailings pond water. Although high costs may make the treatment prohibitive, the research study was successful in reducing selenium concentrations in the laboratory from up to 30 ppm selenium to 0.02 ppm.

Details on the mine sites and specific treatment practices used were not available in the information reviewed for this study.

4.1.4 Rinsing/Treatment Duration

Section 3 described rinsing/detoxification periods of several months; however, in practice a site may require several rounds of rinsing in order to meet State or Federal standards. One problem that frequently has been encountered is that rinsing/treatment is conducted and effluent standards may be met, but subsequent rinsing or testing reveals increased cyanide and other constituent concentrations. (Nevada 1993b) Spring snowmelts have caused effluent concentrations to rise. Several States, as well as BLM, request follow-up effluent sampling after periods of rest or after rainy season/spring snowmelts prior to approving completion of detoxification. (BLM 1992; Idaho 1993, South Dakota 1993) Although the reasons for incomplete or variable rinsing have not been confirmed, Durkin (1990) proposes that non-uniform neutralization or dilution may be factors. A number of facilities have had to switch treatment methods after a chosen method did not reach the desired concentrations. Thus, in practice, rinsing may take many seasons, or years, to complete.

In addition, climatic conditions effect the amount of time needed for closure and reclamation. Cold weather effectively shuts down many operations. Natural and biological treatment methods cease naturally at low temperatures over the winter months. (Schafer and Associates 1990; McGill & Comba 1990; BLM 1992; Higgs 1992)

Furthermore, according to a Nevada Bureau of Water Quality representative, the cyanide rinsing standard of 0.2 mg/l WAD cyanide has been difficult for many operators to achieve, and the mining community would like to see the standard changed. Agglomerated heaps are more difficult to rinse because aggregating the material (lime, etc.) keeps the pH elevated, which in turn makes reduction of pH and detoxification of cyanide more difficult. The Trinity mine near Lovelock, Nevada operated an agglomerated heap; at closure initial WAD cyanide concentrations were 400 - 500 mg/l. The facility proposed using natural degradation to reduce the cyanide concentrations, but has had little success to date at lowering the cyanide levels via natural degradation. A final decision on the Trinity mine was not available; the amount of time since operations ceased also was not obtained. In several instances, the State has issued or is considering variances from the rinsing criteria. (Nevada 1993c)

4.1.5 Water Balance

Water balance can be a concern at some sites. In arid regions, with limited water resources, the amount of water that is necessary to rinse heaps to a required standard may be a significant concern. Conversely, in wet climates like South Carolina, excess water from heavy precipitation can place a strain on system operations and may make draining or revegetating a heap or impoundment very difficult. (ELI 1992) South Carolina has experienced severe problems as a result of weather conditions, such as heavy and persistent rainfall causing flooding, leaks, dam compromises, etc., making closure difficult. South Carolina has also had trouble

with revegetation at the Brewer mine facility heap leach pad; details were not available for this report. (South Carolina 1993). Sudden snowmelt also can affect operations.

4.1.6 Percolation of Solution through Heaps

The presence, or potential for "blind-offs" in heaps may cause incomplete neutralization or treatment. Blind-offs are less permeable lenses or isolated areas of a heap that affect percolation and flow through the heap, leading to preferential paths for fluid migration. Research suggests that preferential flow paths and blind-offs increase with time and volume of liquid. These preferential flow paths can limit the effectiveness of treatment and may leave pockets of contaminants behind in a heap during closure, which then have the potential to leach out after reclamation.

4.1.7 Acid Generation

Acid generation may be a major problem facing many mines. At one time, acid generation at cyanide sites was not considered to be a potential problem as many mining facilities used only oxide ores (not sulfide ores). However, cyanide leaching facilities have reported cases of acid generation. Even tailings that were originally alkaline have subsequently experienced acid generation. Although lime may be added during cyanide leaching, with residuals existing in tailings or agglomerated heaps, the lime component eventually washes away through weathering leaving sulfide compounds to form acid drainage. (Ritcey 1989; California 1993b)

Colorado's Summitville mine, for example, has experienced a number of problems including acid drainage, water in excess of its calculated water balance, liner failure, and inability to reduce silver and copper levels to meet surface discharge limits. Following the operator's bankruptcy, the site is now undergoing costly "removal" action under CERCLA and has been proposed for listing on the NPL. (Danielson and McNamara 1993)

5. REGULATORY PROGRAMS

The following section provides a brief overview of those Federal and state requirements that are specific and unique to waste management at cyanide leach operations, such as programs related to cyanide tailings impoundments, spent heaps and pads, and solution wastewater. The section is not a comprehensive summary of all the regulatory requirements that apply to a cyanide facility but rather, introduces some of the key Federal and State programs involved in the oversight of cyanide operations.

5.1 Federal Requirements

5.1.1 Environmental Protection Agency - NPDES Program

The Environmental Protection Agency's (EPA) National Pollution Discharge Elimination System (NPDES) program requires permits for all point source discharges to surface water. For most industries, technology-based discharge effluent limits have been established using best available technology.

The standard established in 40 CFR 440 Subpart J for mills that beneficiate gold or silver by cyanidation is zero discharge: such mills may not discharge process wastewater unless they are in areas where net precipitation exceeds net evaporation. In such areas, mills may discharge the difference between annual precipitation and evaporation, subject to National effluent limitations for total suspended solids, copper, zinc, lead, mercury, cadmium, and pH, and subject to other standards established on a case-by-case basis.

Because tailings dams may leak, the point at which the zero discharge limitation is applied may be downgradient of the impoundment. In such cases, seepage from the impoundment is collected in ponds and pumped back to the impoundment during the active life of the facility.

It should also be noted that the effluent limitation guideline was developed for mills that use cyanide and predates the widespread use of heap leaching to recover gold. However, the zero discharge standard has been universally applied to heap leach operations. Although there are provisions for permit applicants, on a case-by-case basis, to seek different limits based on "fundamentally different factors" that apply to their discharges relative to those studied by the Agency in setting the standards, to date there have been no known requests for different limits.

In many cases, seepage and runoff from impoundments, spent ore piles, and waste rock piles has not been considered to be a point source discharge and thus has not been subject to NPDES permits. However, EPA and States are currently in the process of developing general NPDES permits for currently unpermitted discharges of these types under the storm water program. This program now requires permits for all point source discharges of storm water from active and inactive mine sites, and general permits began to be promulgated in late 1993.

The Federal drinking water maximum contaminant level (MCL) for cyanide is 0.2 mg/l. In the absence of an effluent guideline for inactive operations, this level is often used as a measurement for acceptable effluent quality following closure.

5.1.2 Bureau of Land Management

The Federal Land Policy and Management Act of 1976 (FLPMA) requires the Department of Interior to prevent unnecessary and undue degradation of the public lands. The Bureau of Land Management Policy for Surface Management of Operations Utilizing Cyanide or Other Leaching Techniques, issued in August 1990, describes minimum acceptable design requirements, mandatory waterfowl death and discharge reporting, and quarterly inspection requirements for facilities located on Federal lands. (BLM 1990a, GAO 1991) A Cyanide Advisory Committee oversees the cyanide policy at BLM.

BLM issued the policy in response to the increased use of cyanide heap leach technology on public lands. The policy outlines general activities and standards to be implemented by the state or district offices. The policy was issued to ensure that operations that use cyanide or other solutions lethal to humans, wildlife, or

livestock are conducted in a manner that ensures the safety and protection of the public and the public lands. (BLM 1990a)

According to BLM, the NEPA process will be used to evaluate impacts of proposed cyanide operations. As with other types of mining, cyanide leaching facilities must file a plan of operation with BLM. Training of BLM personnel has and will continue to be conducted, including inspection and enforcement training, with plans to conduct quarterly inspections of cyanide operations. BLM has plans for a core group of cyanide management experts.

Facility requirements contained in the policy address use of best practicable technology and measures to fence active areas including ditches and conveyances containing cyanide. All tanks containing lethal solutions are to be bermed. Leak detection and recovery systems are required for heaps and solution containment structures. Facilities must have overflow ponds for cyanide solution containment and for runoff from leach pads; containment should be sufficient for the maximum operating water balance plus runoff from a 100-year 24-hour storm event. Weekly samples of sublethal cyanide solutions are to be collected from open containment and transfer structures.

On August 14, 1990 BLM issued a Modification of Bonding Policy for Plans of Operation Authorized by 43 CFR Part 3809. This modification requires operators who use "cyanide/other leachates" to post a bond equal to 100 percent of estimated closure costs. The bonding policy modification was applicable to leach heaps, pads, and cyanide-bearing tailings impoundments and ponds, but did not apply to vat leach facilities using cyanide.

Since the original August 1990 cyanide policy and bonding modification, BLM has issued two additional changes to its cyanide policy. The first change, issued on October 9, 1991, was an additional modification of the Bonding Policy. It removed the vat leach exemption from the 100 percent estimated closure cost bonding requirement. The second change, issued on October 10, 1991, recommended rotation of trained BLM personnel in an effort to improve cyanide inspections.

BLM policy requires bonds for the full cost of reclamation, including heap and solution detoxification and neutralization to State and Federal standards, for all cyanide operations on Federal lands. BLM requires that cyanide solutions and heaps be neutralized or detoxified prior to solution release to the environment. Neutralization of cyanide solutions is also required for any prolonged period of inactivity and for temporary or final closure. Specific concentrations for neutralization or detoxification levels are not specified in BLM policy. Heaps must be neutralized upon completion of each heap. Flushing alternatives may be used, but heap materials and/or discharges must meet the appropriate state and EPA discharge limits. The conditions necessary for release of bond were not addressed in the BLM policy.

Monitoring of groundwater and surface water through closure and final reclamation is required. Specific monitoring requirements such as the frequency, location, chemical parameters, and analytical methods were

not outlined in the policy and are left to the discretion of the state and BLM district offices. Additional details on detoxification, closure, and reclamation of cyanide operations are not addressed in the BLM policy.

In 1992, BLM issued its Solid Minerals Reclamation Handbook with guidance on reclamation of mining sites on Federal and Indian lands (BLM 1992). The manual specifically addresses cyanide heap and vat leach systems and provides general reclamation guidance and approaches. According to the BLM, the mine reclamation plan should cover cyanide detoxification of residual process solutions, ore heaps, tailings impoundments, and processing components. BLM strongly encourages laboratory and pilot test studies of selected/proposed detoxification. Concurrent reclamation during active mining also is recommended. In the Handbook, BLM does not require any specific metal or cyanide concentrations that must be achieved. Criteria are established on a site-specific basis reflecting any special concerns of the area. The Handbook is written as a general "how to" manual as opposed to setting specific requirements of procedures that must be followed. It discusses the various methods of treatment available (hydrogen peroxide, natural degradation with fresh water rinse, alkaline chlorination, etc.) and outlines the various phases of reclamation (treatment of cyanide solutions, disposal of treated solutions, spent heap and tailings, shaping and revegetation, surface water diversions, process ponds, and liner disposal).

BLM recommends allowing an extended period of time, six months or more, between cessation of neutralization and evaluation of effluent when determining the success of neutralization or detoxification. The extended period should cover a spring run-off or substantial precipitation event. Once this has been done, surface reclamation can begin. (BLM 1992)

BLM recommends breaching the heap pad liner or tailings containment dike after detoxification criteria have been met, and adding sized rock to promote infiltration. Precipitation is thus allowed to drain and accumulation of liquids is averted. Accumulation of liquids may generate leachate or adversely affect heap or tailings structural stability. (BLM 1992)

Reclaimed heaps should be reduced in slope to at least 2h:1v, with bench terracing for slopes greater than 200 feet in length. Reclaimed tailings should have flatter slopes in order to resist erosion of fine-grained material (wind or water erosion) and allow for revegetation. (BLM 1992)

BLM (1992) allows for land application of treated rinse solutions and pond water, and mixing of nonhazardous pond sludges with cement and disposal (burial) onsite.

5.1.3 U.S. Forest Service

The Forest Service has not developed a cyanide policy. Cyanide leaching operations are handled in the same manner as any other mining operation on Forest Service land, requiring submittal of a plan of operations to the appropriate district or field office. Each operation plan must address closure and final reclamation activities but there are no specific cyanide requirements for closure and reclamation. The Forest Service does

not require dilution or detoxification to specific cyanide concentrations; each plan of operation varies depending on site operations, terrain, distance to surface water, etc. (GAO 1991; USFS 1993)

5.1.4 National Park Service

The National Park Service has published a cyanide handbook (Environmental Handbook for Cyanide Leaching Projects, June 1986) providing general guidance on the fundamentals of cyanide leaching and environmental safety and controls. The handbook provides a brief overview of cyanide decommissioning and reclamation, but specific standards, such as detoxification requirements or cyanide concentrations, have not been published. The National Park Service appears to defer to individual states, or other local authority, for specific cyanide guidance and regulatory authority, but may be involved on a case-by-case basis depending upon site-specific concerns. (National Park Service 1986)

5.2 State Requirements

In the following paragraphs, a summary of applicable state requirements for cyanide operations are reviewed. This discussion does not include a complete characterization of all applicable mining programs. An attempt has been made to highlight those factors that are unique to cyanide operations that may vary from state to state, such as rinsing criteria. Construction design and operating standards for heaps and tailings are briefly discussed, as they affect closure and reclamation. The requirements for California, Colorado, and Montana are up to date as of 1992. The Agency is aware that substantive changes in the regulations in these states have been made since that time. For more information, the reader should contact the state.

States do not have prescribed technologies that must be used for detoxification, but rather rely on performance standards requiring detoxification to specific criteria. If a site is unable to meet criteria, a state will often issue a variance based on an alternative treatment method or treatment standard. Alternatives are typically supported by pathway fate and transport analysis or modeling. For detoxification and closure, monitoring parameters typically include WAD, free and/or total cyanide, pH, and metals.

Table 3 provides a comparison summary of various state treatment or detoxification criteria for wastes and highlights unique reclamation and/or bonding requirements. The table illustrates that there is not a uniform standard in terms of concentration or constituent specie. Many states use these levels as guidelines and may issue site-specific variances if a facility is unable to meet these levels. Several states are debating between WAD cyanide and free or total cyanides, thus, the cyanide species/levels presented in Table 3 may be subject to change. Typically, once detoxification levels are met, and approval is received from the State, final closure begins, followed by reclamation of the site.

5.2.1 California

The California Regional Water Quality Control Boards (RWQCBs) oversee rinsing and closure activities. Once the rinsing standards have been met, reclamation is turned over to the County, and if applicable, to the Federal land management agency. Information on the specific requirements for release of bonding for mine sites (cyanide operations) in California was not available.

In California, selection of both rinsing/neutralization and detoxification methods is left to facility discretion. The State requires that for detoxification to be considered complete, the residual cyanide in the tailings, leach pad, or solution pond must not exceed the limits listed in Table 3 (for liquids: total cyanide 1.0 mg/l; WAD cyanide 0.2 mg/l)¹. The state has separate requirements for solid samples, which must meet the following levels: soluble WAD cyanide 0.5 mg/l; soluble total cyanide 2.5 mg/l; total cyanide² 10.0 mg/l.

**Table 3. Summary of State Requirements:
Cyanide Heap Leach and Tailings Impoundment Closure and Reclamation**

State	Treatment Criteria	Reclamation/Bonding
California	Residual cyanide in heaps, tailings or solution ponds must meet the following prior to discharge of wastes: Liquid component: <ul style="list-style-type: none">• WAD cyanide: 0.2 mg/l• total cyanide: 1.0 mg/l Solid component: <ul style="list-style-type: none">• soluble WAD cyanide: 0.5 mg/l• soluble total cyanide: 2.5 mg/l• total cyanide³: 10.0 mg/l	Where feasible State requires spent ore to be used as backfill in mine pits for reclamation.
Colorado ⁴	Detoxification standards are determined on a site-specific basis by permit writer ⁵ . They are based on ambient water quality, characteristics and uses of water in the area, and projected effluent characteristics; may address cyanide and metals. As of mid 1994, Colorado is finalizing regulatory requirements for cyanide operations.	Same as other mining operations. (However, costs estimates must reflect cyanide detoxification.)

¹ Note the current WAD cyanide standard has been changed from the 1987 standard of 0.5 mg/l.

² Total cyanide after extraction of soluble WAD and soluble total cyanide. Source RWQCB, 1987.

³ Total cyanide after extraction of soluble WAD cyanide and soluble total cyanide. (RWQCB, 1987)

⁴ California Regional Water Quality Board "Cyanidation Requirements for Cyanidation Process Wastes", April 22, 1987.

⁵ The State of Colorado has published "Guidelines for Cyanide Leaching Projects," March 1992, to present an overview of the considerations necessary in preparation and review of reclamation permits for cyanide leaching operations.

**Table 3. Summary of State Requirements:
Cyanide Heap Leach and Tailings Impoundment Closure and Reclamation (Continued)**

State	Treatment Criteria	Reclamation/Bonding
Idaho ⁶	<p>Prior to disposal or abandonment of leached ore, concentrations of WAD or free cyanide and other pollutants in process-contaminated water draining from the leached ore must be:</p> <ul style="list-style-type: none"> reduced to a level set by the permit writer based on disposal method, location, and potential for surface water and groundwater contamination; <p>or</p> <ul style="list-style-type: none"> pH between 6.5 and 9 (stabilized) <p>Seasonal closures must also address water balance.</p>	<p>Requires permanent closure plan and possible post-closure monitoring. No reclamation requirements specified in cyanidation regulations⁸.</p> <p>Bonding for permanent closure required in cyanidation regulations.</p>
Montana	<p>Water Quality Act requires no discharge from cyanide operations into State waters. Metal Mine Reclamation Act (includes new standards for small cyanidation facilities):</p> <ul style="list-style-type: none"> Based on permit writer's discretion. to levels considered acceptable based on under applicable water quality standards. 	<p>Same as other mining operations, except cyanide operations that would normally qualify for the small miner's exclusion are subject to operating and reclamation requirements.</p>
Nevada	<p>General Performance Standard that facilities may not degrade the waters of the State. Surface water quality is set by NRS 445.253. Groundwater is set at Federal or State drinking water standards and WAD cyanide at 0.2 mg/l.</p> <p>Heaps: Spent ore must be rinsed until effluent reaches</p> <ul style="list-style-type: none"> WAD cyanide: 0.2 mg/l pH: between 6 and 9 Remaining solids tested using Meteoric Water Mobility Test <p>Tailings (vat leaching)¹⁰: For impoundments that do not have underdrainage collection systems, solids must be tested using Meteoric Water Mobility Test.</p>	<p>Pond sludges, heap solids must be tested using Meteoric Water Mobility Test during closure prior to reclamation.¹¹</p> <p>Reclamation similar to other mining operations.</p>

⁶ Idaho cyanidation rules became effective January 1, 1988. Facilities existing as of the effective date are not subject to the requirements.

⁷ In Idaho, tailings impoundments that require recycling of process water to prevent a point source discharge may be exempt by the State.

⁸ It is unclear if Idaho subjects cyanidation facilities to the reclamation requirements of the Idaho Surface Mining Act.

⁹ In Nevada, variances are available.

¹⁰ Cyanidation tailings generated from tank or vat leaching are not specifically called out in the Nevada regulations. The treatment standard for cyanidation tailings prior to discharge to the tailings impoundments has not been obtained.

¹¹ In Nevada, units that have a history of liner integrity problems may be required to test underlying soils using the Meteoric Water Mobility Test.

**Table 3. Summary of State Requirements:
Cyanide Heap Leach and Tailings Impoundment Closure and Reclamation (Continued)**

State	Treatment Criteria	Reclamation/Bonding
South Carolina	<p>Based on permit writer's discretion. Current criteria:</p> <ul style="list-style-type: none"> • free cyanide: 0.2 mg/l¹² <p>In practice, level to which constituents (including CN) are reduced determine how post-closure leachate and wastes may be managed.</p>	<p>Closure required as part of reclamation.</p> <p>Under Mining Act, bond for "affected area" is approximately \$1000/acre. However, under Pollution Control Act, (which does not specifically provide for bonding), one mine in the State was required to post \$10 million financial assurance.</p>
South Dakota	<p>Heaps: spent ore can be off loaded when effluent or pore water meet:</p> <ul style="list-style-type: none"> • WAD cyanide less than 0.5 mg/l • pH of 6.5 to 8.5 • all other parameters must meet existing State standards or ambient concentrations • alternative treatment criteria available • Cyanide based on effluent samples taken at base of heap. Criteria other than cyanide may be effluent samples or pore water extracted from solid sample analysis. <p>Tailings (vat leach)</p> <ul style="list-style-type: none"> • information not obtained 	<p>Same as other mining operations.</p>

¹² South Carolina is currently considering changing limit from free cyanide to total cyanide.

According to State personnel, experience has shown that particle size influences detoxification of heaps. When a heap is composed of run-of-mine ore, rinsing can be completed within 4 to 6 days with cyanide levels dropping to 1.0 mg/l; a long rinse may take as long as 6 months, however. Crushed and agglomerated ores are more difficult to rinse. (California 1993c)

Mines are also required to determine the acid neutralization versus the acid generation potential of their ore and waste rock as part of their permit requirements. (California 1993b)

Monitoring requirements for each site are typically addressed in Water Discharge Requirement (WDR) permits. These permits are required from the Regional Water Quality Control Boards for all discharges. Monitoring requirements are site-specific, depending on site conditions.

5.2.2 Colorado

The Colorado guidelines do not require specific methods for rinsing, neutralization or detoxification. Detoxification standards for cyanide (heaps and ponds) are established on a site-by-site basis between the applicant and the Division of Minerals and Geology. Colorado is currently drafting regulations for cyanide operations. Factors taken into consideration during the permit review process include water balance of process and detoxification solutions, ambient water quality, characteristics and uses of the water in the area, and projected effluent characteristics. If residual metals are anticipated to be a problem, then appropriate treatment standards are also developed for those constituents. (Colorado 1992a)

Specific practices for cyanide leaching are addressed in a Colorado-issued guidance manual for State staff entitled "Guidelines for Cyanide Leaching Projects" (March 1992). The cyanide guidelines recommend double liners on all surfaces that will potentially come in contact with a cyanide solution, including all pads, ponds, piping and conveyance systems, and pretreatment areas. Soil layers are allowed as double liners if the soil meets the "impermeable" standard of 1×10^{-6} cm/sec; however, to be used as a lower liner in a pond, a soil liner must have a maximum permeability of 1×10^{-7} cm/sec. Colorado has not set a permeability standard for synthetic liners. (Colorado 1992a; ELI 1992)

The State also requires leak detection systems, installed between the upper and lower liners at all leach pad areas and pond areas. Although double liners are not specifically required around tanks or vats, a method of detecting leakage must be provided, such as a permeable zone overlying a low-permeability layer. (Colorado 1992a)

Colorado has approximately 17 active cyanide leach sites, the majority (12) of which are permanent heap leach pads. There are three vat leach operations and one each of valley and on/off pads. (WGA 1991b)

For cyanide operations, Colorado requires surface and groundwater quality monitoring, three to four times annually, during reclamation as well as during active operations. (Colorado 1992a)

Bonding requirements for cyanide operations are the same as for other mining activities, but calculation of the costs must address detoxification of the ore and process solutions by including: an estimation of the volume of solutions in ponds during detoxification, the average residual cyanide in ore for each rinsing, and calculation of the amount of detoxification agent for each rinse until the detoxification standard is reached. (Colorado 1992a)

Colorado reclamation standards are broadly defined. Reclamation must be such that "all refuse and acid-forming or toxic producing materials that have been mined shall be handled and disposed of in a manner that will control unsightliness and protect the drainage system from pollution." (ELI 1992) The Colorado guidelines "require" geochemical testing of tailings, including acidification/neutralization testing (acid/base potential) and recommend kinetic tests such as humidity cell or column tests. Depending on the test results, appropriate design measures can be determined. (Colorado 1992a)

Heap reclamation varies depending upon the type of heap used. The Colorado guidelines recommend free draining and expanding heaps be leveled to blend with the ground surface. The State recommends grading the top of valley heaps and capping them with an impermeable cover. Drilling holes through a valley heap's liner system is also suggested to allow "natural passage of water down the valley". For valley fill leach pad areas on top of bedrock, drilling a horizontal drain through the impoundment may be done to reestablish drainage. Reconstructed channels may be necessary through valley areas to reestablish "natural" surface drainage systems. (Colorado 1992a)

For closure and reclamation of ponds, the Colorado guidelines state that "After all the solution in the pond has been eliminated through spray evaporation or land application, stabilization of the pond areas can commence." As discussed above, detoxification standards are determined on a site-specific basis. Pond stabilization measures may include folding synthetic pond liners over any remaining sludge, or excavating the remaining sludge, followed by grading of the surface contours. Additional details or guidance concerning spray evaporation and land application is not provided in the state manual. (Colorado 1992a)

It should be noted that (as of Spring 1993) the Colorado legislature was considering a major revision to the Mined Land Reclamation Act. In addition, the Mined Land Reclamation Board placed a moratorium on approval of new cyanide operations in early 1993 (the status of the moratorium was not determined).

5.2.3 Idaho

Idaho has a program for permitting the construction, operation, and closure of cyanide operations that applies to new facilities (effective January 1988). For facilities in existence prior to 1988, the existing general mining (not cyanide-specific) regulations apply. (Idaho Title 1 1992)

New cyanide operations are required to meet general design standards for cover containment, impoundments, liner criteria, and storage requirements. Site-specific determinations can be made if the State determines that some parameters are not applicable based on ore, operations, or other site-specific factors. Surface

impoundments must have "efficient leak detection" and "adequate leak recovery"; however, tailings structures more than 30 feet high are exempt from the impoundment requirements (subject to Idaho Code Title 42, Chapter 17). (ELI 1992) Leach pads and impoundments are required to have a hydraulic liner designed for a maximum permeability coefficient of 10^{-7} cm/sec; clay liners are also to have a minimum thickness of 12 inches.

Idaho requires a monitoring strategy in each cyanide operation plan addressing baseline water quality (surface and groundwater), proposed monitoring, leak detection, and emergency response procedures. Ground water, and if applicable, surface water, monitoring is required at all cyanide operations. Duration of monitoring through closure, reclamation and post-reclamation is not identified in the regulations. (Idaho Title 1 1992)

Proposals for land application or economic reuse of cyanide solutions must be included with the permit application. Details on land application are not specifically addressed in Idaho's Rules and Regulations for Ore Processing by Cyanidation.

Several seasonal heap leach facilities operate in Idaho. The State has separate requirements for seasonal, temporary and permanent closure. Seasonal closure requires an increase in freeboard to allow for seasonal runoff and snowmelt. Cyanide concentrations are to be reduced and pH controlled (6.5-9.0) in solution and process waters during seasonal closure. A temporary closure plan is submitted for temporary closure; it details the procedures and schedule for treatment and drainage control. Permanent closure activities are to be included in the operation permit application. (ELI 1992)

Prior to disposal or abandonment of the spent ore, process-contaminated water drained from leached ore must be stabilized at a pH of 6.5 to 9.0, or WAD cyanide levels are to be reduced to 0.02 mg/l. If WAD cyanide is used as the determining value, then other pollutants must be reduced to an appropriate level based on disposal criteria. The other pollutants include those addressed by surface, drinking or other water quality standards that the State deems appropriate on a site specific basis. (Idaho Title 1 1992) Financial assurance for cyanide operations is released when the facility completes permanent closure in accordance with an approved plan. (Idaho Title 1 1992)

5.2.4 Montana

In Montana, all cyanide operations are subject to the general regulations for mining operations adopted in 1980. Each mine must obtain an operating permit that addresses operations, practices, closure and reclamation. In addition, Montana has a permitting program for small cyanide mines less than five acres. The regulations for small mine cyanide operations are more detailed than the general operating permits standards. (WGA 1991b)

In practice, the Montana Department of State Lands is using the same standards for both small and full-size cyanide operations. The technical standards promulgated for small cyanide operations are applied to full-size operations by the permit writer who issues the operating permit. Montana has approximately eight active,

full-scale cyanide operations (requiring permits), three of which are vat leach and five are heap leach (permanent pads). (WGA 1991b)

Cyanide operations must have a remedial action plan for controlling and mitigating discharges; must design and construct diversions and sediment impoundments capable of withstanding a 10-year, 24-hour storm event; must install a leak detection system to monitor WAD cyanide, pH, and electrical conductivity; must have groundwater monitoring wells; develop a wildlife exclusion plan; and construct cyanidation facilities to withstand a 50-year, 24-hour storm event. Monthly construction reports and as-built drawings must be submitted for ponds, tailings disposal units, and other facilities. (ELI 1992)

5.2.5 Nevada

Nevada is one of the leading gold producing states, with over 100 active cyanide leach operations¹³. Nevada's Water Pollution Control Law has cyanide performance standards for groundwater: a facility may not allow cyanide concentrations in groundwater to exceed 0.2 mg/l WAD cyanide. (Nevada 1990) Nevada also has a policy of zero discharge to surface waters from cyanide facilities (this is common to the other States' NPDES programs as well).

Guidelines specific to cyanide operations for closure and reclamation are outlined in the Nevada Department of Environmental Protection's (DEP) "Evaluations for Closure". All mining permits require stabilization of tailings and spent ore during closure. For materials that have been beneficiated by cyanide, both free and WAD cyanide analysis must be conducted.

At the end of active use, tailings and impoundment materials should be sampled and characterized. Spent ore from cyanide heap leaching methods are to be rinsed until weak acid dissociable (WAD) cyanide levels in the effluent rinse water are less than 0.2 mg/l; the pH of the effluent rinse water is between 6 and 9; and any runoff from spent ores piles would not degrade the waters of the State. Cyanide rinsing standards apply to spent ore whether it is left on pads or removed from pads. (ELI 1992) After a heap has met the rinsing standards, it is allowed to drain. When drained, samples of the heap are collected, usually by drilling, and tests are conducted to simulate the effect of fresh water percolating through the heap. This is known as the Meteoric Water Mobility Test. (Nevada 1993a)

Nevada requires (by permit) the Meteoric Water Mobility Test for pond closure at cyanide operations, and requires sites with a history of liner integrity problems to collect subsurface soils for analysis. Closure of ponds in-place often involves folding the synthetic liner over the remaining sludge/residue, backfilling with soil followed by regrading and revegetation.

¹³ Nevada has approximately 90 permanent heap pads, 33 vat leach, 2 on/off pads, and 3 valley leach operations according to a 1991 summary by the Western Governors Association. (WGA 1991b)

Closure is considered complete when the facility and mined areas have been stabilized and no longer have the potential to degrade waters of the state¹⁴. Variances may be granted if the rinsing standards cannot be met by a facility and the facility provides alternative measures to inhibit migration of runoff. Once a heap or pond has been chemically stabilized (as demonstrated by the Meteoric Water Mobility Test), then the State staff sends a letter to the facility allowing them to proceed with reclamation.

In the Evaluations for Closure, Nevada specifies that for tailings impoundments, the saturation and permeability of the tailings be determined and for underdrainage collection systems, the quality and quantity of the underflow solution are to be defined before final closure. Tailings without underdrainage collection systems are to be cored and analyzed by the Meteoric Water Mobility Test. The extent of capping and drainage control methods will be based on the results of the underdrainage analysis. (Nevada 1990) Approximately ten cyanidation sites have been satisfactorily closed and are ready for, or have started, reclamation. (Nevada 1993a)

Reclamation standards are site-specific; no design standards are prescribed in the law or regulations. Heap leaches and tailings may be regraded to enhance structural integrity, reduce runoff, reduce infiltration, and control erosion, or they may be covered with waste rock, topsoil, or growth medium, revegetated, and runoff diverted. (ELI 1992)

The Nevada Department of Wildlife began a permit program for industrial ponds, including tailings impoundments and all cyanide process ponds. The program was created in order to substantially reduce, or eliminate, wildlife mortality associated with mining ponds. (GAO 1991) Numerous birdkills during the 1980s from cyanide ponds prompted enactment of the State law to protect wildlife (effective 1989). The required Department of Wildlife industrial pond permit (also referred to as the toxic pond permit) requires either fencing and covers on all ponds or use of dilution/neutralization. Nevada Department of Wildlife frequently accepts dilution or neutralization of free cyanide to below 50 ppm as sufficient to avoid mortalities. (WGA 1991b; ELI 1992)

5.2.6 South Carolina

The Department of Health and Environmental Control (DHEC) issues construction permits for industrial wastewater treatment systems, including mining process wastewater ponds and rinse systems for cyanide leaching operations, and regulates discharges to surface water and groundwater. The Land Resources and Redevelopment Division (LRRD) issues permits for operational components, including impoundments and heaps, and requires full reclamation.

During rinsing of heaps, quarterly reports must be submitted to DHEC and the LRRD. Rinsing standards for leached ore are being considered by the State for regulatory development, and permeability standards for

¹⁴ The state's Meteoric Water Mobility procedure is used to determine the potential to degrade waters of the state. ELI 1992.

operating units also may be developed. The current detoxification trigger is 0.2 mg/l free cyanide, but the State is considering changing this to total cyanide. Core samples of the heap must be analyzed before closure can be considered complete. (South Carolina 1993b)

There are no specific regulatory standards for closure of cyanide operations, and each case is handled on a permit-by-permit basis. DHEC and LRRD approval is needed prior to conducting closure activities, and a deed record of cyanide unit locations is required. At present, there are four operating cyanidation units in South Carolina; none has undergone complete closure, although several have conducted, or are conducting, rinsing. Until firm standards are developed, site-specific considerations drive most State decision-making. For example, the means by which a facility may manage post-operational heap leachate (e.g., discharge to surface water, impounded in pits, treated) depend on the effluent quality achieved.

When the decommissioning (closure) requirements have been met, administrative responsibility for the mine shifts from the DHEC to the LRRD. Once a heap has met the detoxification and closure requirements, it must, at a minimum, re-slope to 3:1 and revegetate with perennials. The state is considering lengthening the time needed to demonstrate revegetation success from two years to some longer period. (South Carolina 1993a)

Legislation under development (the Solid Waste Management Act) may broaden the State's definition of "industrial solid waste" to include chemically-altered materials, including wastes from cyanidation operations, which would then subject mining wastes to solid waste disposal permit requirements. (Joy 1990)

One cyanide operation in South Carolina with on/off pads has a State industrial solid waste permit for disposal of spent, rinsed ore that is off-loaded but that does not meet the rinsing standards of the site's wastewater construction permit. A decision on whether other cyanidation operations will require an industrial solid waste disposal permit has not been determined. The State will evaluate the issue during closure of those other cyanide operations. (ELI 1992)

5.2.7 South Dakota

Concerns over the impacts of surface mining led to a State moratorium on new large-scale gold and silver mines in South Dakota, effective in 1992. One of the instituted reforms was a requirement for large-scale cyanide operations to develop contingency plans and obtain sufficient financial assurance to cover releases to the environment, and submit annual reports listing annual cyanide use. (ELI 1992)

Permitting for a typical heap leach facility would involve pre-submission meetings, submission of the permit application, a socio-economic study, a completeness review, technical review, a public notice and a public hearing before the South Dakota Board of Minerals and Environment. (WGA 1991b)

South Dakota mining laws, regulations, and permit conditions require that spent ore be adequately neutralized and designated as suitable for disposal before off-loading from heap leach pads. Heaps must be rinsed until treatment standards are reached. (Durkin 1990)

Prior to detoxification, effluent or pore water from the ore must be characterized for cyanide, metals, anions, cations, pH, radioactivity and total dissolved solids. The South Dakota Department of Environment and Natural Resources (DENR) then uses these results to designate key parameters for an individual site to monitor throughout the treatment/neutralization cycle. Spent ore is considered suitable for disposal when the effluent meets the criteria listed in Table 3.

South Dakota DENR requires that neutralization and off-load criteria be based on effluent samples collected at the toe of the spent ore heap or analysis of leachate extracted from a representative solid sample (pore water) taken from the spent ore heap. (Durkin 1990)

If detoxification (treatment) of tailings is not successful and the operator wishes to try a new treatment method, a new treatment plan must be submitted to DENR. In cases where the treatment criteria cannot be achieved, DENR may develop alternate, site-specific criteria, or tailings may be reclaimed such that infiltration, percolation, and discharge are minimized, as indicated by appropriate pathway and fate analysis. (Durkin 1990)

The South Dakota Water Pollution Control Law has set a regulatory groundwater standard for WAD cyanide at 0.75 mg/l. Concentrations detected at or above this level prompt remedial groundwater investigations. (ELI 1992)

The State has five leach operations, of which three are on/off pads. The fourth is a permanent heap pad and the fifth is a vat leach operation (WGA 1991b). With detoxification of heap leaches, the State's experience has shown that 2.5 pore volumes are required before effluent concentrations are within the required standards. (South Dakota 1993)

During reclamation of heap leach operations, the spent ore must be used as backfill in the mine pits where feasible. Reclamation of in-place tailings piles must not block drainage pathways.

6. CASE STUDIES

Selected case studies at active sites are presented in this section. The active sites selected as case studies were not selected as either good or bad models, but rather to examine a range of cyanide treatment techniques. The three active case studies highlight a vat leach operation with INCO treatment of tailings slurry, a large leach heap operation with several heap pads, and a site using biological treatment by bacteria. Material for the case studies came from publicly available documents, and file materials collected from the respective State regulatory offices. The Agency has not evaluated the efficiency of any of the methods presented. This section was developed for informational purposes only.

6.1 Hecla, Yellow Pine, Idaho

Hecla Mining Company completed gold extraction from its heap leach pad at Yellow Pine, Idaho in 1992 (Minerals Today). Currently, the facility is detoxifying the cyanide in the spent ore by applying a bacterial biological treatment method to the heap.

The bacterial solution is applied to the spent heap using sprinklers to spray the top of the heap. The solution then percolates through the spent ore with bacteria consuming the cyanide as it progresses. After the solution passes through the heap it is collected in a process pond and then recycled back through the heap. At the end of treatment, the solution pond will be allowed to evaporate, materials (sludges) will be sampled and analyzed, and the unit will be closed in place by folding the pond liner over any remaining sludge, contouring, and revegetating. Information on the type of bacteria, additional nutrients required, and the developer of the process used by Hecla have not yet been obtained. (Idaho 1993)

After treatment, effluent from the heap reached the 0.2 mg/l state standard for cyanide during the fall of 1992. The Idaho DEQ wants to review cyanide levels through one wet rainy season prior to approving the start-up of reclamation activities. The facility planned to collect effluent samples during spring sampling. Depending on the results of this sampling, the state may approve initiation of reclamation for Fall 1993. (Idaho 1993)

The detoxified heap may not require capping. The fourth (top) tier of the heap will be removed and used to regrade and contour the heap. A berm will be constructed around the top of the heap to prevent runoff erosion from destroying the steep slopes of the heap. The liner beneath the heap will not be broken with numerous perforations, but approximately three spots will be used to drain any percolated material to the ground. The state will require 5 to 10 years of groundwater monitoring of onsite wells (for cyanides and metals). (Idaho 1993)

An Idaho representative (Idaho 1993) stated that the biological cyanide destruction process has appeared to work well at the Yellow Pine facility. The site has been able to meet the 0.2 mg/l WAD cyanide standard for heap effluent, although the state is still waiting to see the results after a wet season, before it approves closure. Metals have not been a problem at the site, although the state representative credits this to the composition of the ore rather than the result of the biological treatment process.

6.2 Zortman Mining, Landusky Heaps, Montana

Zortman Mining, Inc. of Zortman, Montana (a subsidiary of Pegasus Gold Corporation) operates several heap leach pads, a processing plant, and barren and pregnant leachate solution ponds. The Landusky reclamation plan was approved in 1990 by the BLM and Montana Department of State Lands. The heaps are low grade run-of-mine ore (neither crushed or agglomerated) that were leached in 25-foot high lifts. (Fitzpatrick 1992; Schafer and Associates 1991a) A Montana state file lists the site as one of the 13 largest metal mines in Montana, processing 75,000 tons of ore a day. The heaps and tailings cover 175 acres and contain 60 million tons of material.

Being one of the first mines permitted under the 1974 Montana Metal Mining Reclamation Act and the first large-scale gold heap leaching operations in the US (operations began in 1979), the Zortman/Landusky site represents the evolutionary changes in heap leach technology and regulatory requirements through the past two decades. The first heap pad constructed at the site consisted only of a 12-inch clay layer, side berms, and a simple reclamation plan. With each successive addition or modification there came additional permit stipulations. The operators also voluntarily added more engineered controls. In 1990, the State required the heaps to be neutralized to a cyanide level of 0.22 mg/l WAD cyanide, and declared that heap slopes greater than 2:1 would no longer be acceptable.

A pilot study of rinsing techniques was begun at the Zortman Landusky heaps in 1982. It was followed with a cyanide degradation study in 1986. These investigations were conducted as part of the detoxification and closure program for the three heaps. The rinsing and degradation studies found that rinsing of the heaps was an effective means of accelerating (compared to natural degradation) cyanide, metal, and nitrate removal. (Schafer and Associates 1991a)

Prior to rinsing of the heaps, the Landusky heaps were allowed to degrade naturally (through natural processes of volatilization, oxidation, formation of thiocyanate, and biodegradation). Natural degradation was followed by rinsing of the heap with fresh water to reduce WAD cyanide concentrations in solution. (Schafer and Associates 1991a)

The facility concluded that rinsing with one pore volume removes 50 to 90 percent of cyanide and metals in pore water and was an effective means of accelerating the rate of cyanide and metal degradation in heaps. (Schafer and Associates 1991a)

During the rinsing of the Landusky heaps, however, several issues were raised: the amount of solution retained in the heap, long-term seepage from decommissioned and reclaimed heaps, the long-term degradation of cyanide in heaps, and the attenuation of metals in heaps. During investigations at the site, evidence suggested that movement of water through the heap was rapid and homogeneous. (Schafer and Associates 1991a)

Periodically, Landusky land applies neutralized solution to a specified parcel of land at the site. In 1987, during one round of land application four million gallons were applied during a five day period. Cyanide concentrations of the water applied to the ground were above 3 mg/l (exact concentrations were not obtained for this report).

6.2.1 McCoy/Cove Mine, Echo Bay Mining Company, Nevada - INCO process

The McCoy/Cove Mine, near Battle Mountain, Nevada, operates a vat leach operation for extraction of gold. The facility added an INCO cyanide treatment system in 1990 to its operations after experiencing more than 1000 water-fowl deaths caused by migratory birds drinking out of its cyanide tailings impoundment (such deaths are in violation of the U.S. Migratory Bird Treaty Act).

At the McCoy mine, the INCO process is used to remove cyanide from the tailings pulp after gold has been recovered from the milling process. Prior to the use of INCO, the spent tailings were discharged directly to a tailings pond. The liquid fraction of the tailings was reused as make-up in the leaching process. The cyanide-containing liquid in the 145 hectare tailings pond attracted the migratory birds in a desert area with few open bodies of water.

The system treats tailings pulp (thickener) underflow containing 268 kg WAD cyanide/hour in two parallel reactors (40 percent solids; 8,500 stp mill throughput) to reach a target residual cyanide level of 25 mg/l WAD cyanide (it can reach 5 mg/l WAD cyanide, if necessary). Other INCO references suggest that the McCoy/Cove effluent has total cyanide levels below 10 mg/l. Periodic WAD cyanide analysis, as well as SO₂ feed, slurry flow rate, pH, and percent solids, are monitored. Tailings are disposed of in a tailings impoundment where WAD cyanide levels are monitored daily, ranging from 4 to 7 ppm. (Devuyst 1992; INCO 1992) The facility has cut its cyanide consumption by reusing cyanide recovered from the INCO process.

7. REFERENCES

- Ahsan 1989. "Detoxification of Cyanide in Heap Leach Piles Using Hydrogen Peroxide", Ahsan, M Q, et al., In *World Gold*, proceedings of the First Joint SME/Australian Institute of Mining and Metallurgy Meeting, R. Bhappu and R. Ibardin (editors), 1989.
- Altringer 1991. Altringer, P B, Lien, R H., Gardner, K R, Biological and Chemical Selenium Removal From Precious Metals Solutions, proceedings of the Symposium on Environmental Management for the 1990s, Denver, Colorado, February 25-28, 1991.
- Berkeley 1988. University of California at Berkeley, Mining Waste Study, Final Report, prepared for the California State Legislature, July, 1988.
- BLM 1990a. US Department of the Interior, Bureau of Land Management, "Policy for Surface Management of Mining Operations Utilizing Cyanide or Other Leaching Techniques" Instruction Memorandum No. 90-566, Washington, DC, August 1990.
- BLM 1990b. US Department of the Interior, Bureau of Land Management, "Modification of Bonding Policy for Plans of Operation Authorized by 43 CFR 3809" Instruction Memorandum No. 90-582, Washington, DC, August 1990.
- BLM 1992. US Department of the Interior, Bureau of Land Management, *Solid Minerals Reclamation Handbook*, BLM Manual Handbook H-3042-1, 1992.
- BLM 1993. Personal communication between Bill Lee, Bureau of Land Management, and Michelle Stowers, Science Applications International Corporation, on April 26, 1993.
- BOM 1978. US Department of the Interior, Bureau of Mines, *Processing Gold Ores Using Heap Leach-Carbon Adsorption Methods*, Information Circular No. 8770, Washington, DC, 1978.
- BOM 1984. US Department of the Interior, Bureau of Mines, Gold and Silver Leaching Practices in the United States, Information Circular No. 8969, Washington, DC, 1984.
- BOM 1986. US Department of the Interior, Bureau of Mines, *Precious Metals Recovery for Low-Grade Resources*, proceedings of the Bureau of Mines Open Industry Briefing Session at the National Western Mining Conference, Denver, Colorado, February 12, 1986. Information Circular No. 9059. Washington, DC.
- BOM 1991a. US Department of the Interior, Bureau of Mines, 1989 Minerals Yearbook, Washington, DC, 1991.
- BOM 1991b. US Department of the Interior, Bureau of Mines, *Mineral Commodities Summaries, 1990*, Washington, DC, 1991.
- BOM 1993. Personal communication between Sandra McGill, U.S. Bureau of Mines, Reno, Nevada Office, and Joe Rissing, Science Applications International Corporation, on January 21, 1993.
- Brooks 1992. Reclamation of the Timberline Heap Leach: Tooele County, Utah, USDI Bureau of Land Management, Technical Note # 386, by Steven J Brooks, 1992.

- CA DHS 1988. California Department of Health Services, Toxic Substances of Control Division, Alternative Technology Section, Waste Evaluation Unit, A Study of Heavy Metal Leaching of Mine Waste Tailings, September 1988.
- Caldwell, Caren S. 1993. Letter to Steven Hoffman, Office of Solid Waste, USEPA from Pintail Systems, Inc. September 1, 1993.
- California 1993a. Personal communication between Jehiel (Jay) Cass, California Regional Water Quality Control Board, Lahonton Region, and Joe Rissing, Science Applications International Corporation, on January 12, 1993.
- California 1993b. Personal communication between Richard Humphreys, California Regional Water Quality Control Board, and Joe Rissing, Science Applications International Corporation, on January 19, 1993.
- California 1993c. Personal communication between Neil Krull, California Water Quality Control Board, Palm Desert, and Joe Rissing, Science Applications International Corporation, on January 25, 1993.
- Calgon Carbon Corporation Undated. *Granular Carbon For Gold Recovery*. Brochure. Pittsburgh, PA.
- Carson Hill 1990. Report of Final Closure, Leach Unit 1, Carson Hill Gold Mine, Calaveras County, California, Western Mining Corporation/Carson Hill Gold Mining Corporation, October 24, 1990.
- Carson Hill 1991. Report of Final Closure, Leach Unit 2 - Detoxification, Carson Hill Gold Mine, Calaveras County, California, Adrian Brown Consultants, Inc., July 30, 1991.
- Carson Hill 1992. Report of Final Closure, Leach Unit 3 - Detoxification, Carson Hill Gold Mine, Calaveras County, California, prepared by Adrian Brown Consultants, Inc. for Western Mining Corporation (USA), Carson Hill Operation, January 21, 1992.
- Carson Hill Undated. Excerpts from the geology and climate sections of the Feasibility Study on the Carson Hill Mine Project. (Full citation, including date, not provided.)
- Colorado 1992a. "Guidelines for Cyanide Leaching Projects", Colorado Department of Natural Resources, Mined Land Reclamation Division, March 1992.
- Colorado 1992b. Notice of Violation and Order, Battle Mountain Resources, Inc., Permit No. M-88-112, Colorado Mined Land Reclamation Board, May 28, 1992, AG Alpha No. NRLRICACO, AG File No. E9216915.88, and Notice of Probable Violation Abatement Requirement.
- Damon, Smith and Mudder 1992. Geochemical Study of Leach Pad Cyanide Neutralization, Brohm Mining Corporation, South Dakota, presented at the SME Annual Meeting, Phoenix, Arizona, February 24-27, 1992. SMME Preprint No 92-173.
- Danielson and McNamara 1993. The Summitville Mine: What Went Wrong, Luke Danielson and Alix McNamara, March 25, 1993.
- Degussa 1988. Advances in the Treatment of Gold Mill Effluents with Hydrogen Peroxide, by Andrew Griffiths, Degussa Corporation, paper presented at the 1988 Annual Meeting of the Society of Mining Engineers, Phoenix, Arizona, 1988.

- Devuyst 1990. Inco's Cyanide Destruction Technology, Devuyst, E A, et al., Society For Mining, Metallurgy, and Exploration, Inc., September, 1990. Preprint No. 90-406.
- Devuyst 1992. Recent Applications of the INCO SO₂/Air Cyanide Removal Process, E A Devuyst, R D Vergunst, P F Iamarino, R J Agius, INCO Exploration and Technical Services, paper presented at the 94th Annual General Meeting of the CIM, Montreal, April 27-29, 1992.
- Doyle 1990. *Mining and Mineral Processing Wastes*, proceedings of the Western Regional Symposium on Mining and Mineral Processing Wastes, Berkeley, California, May 30-June 1, 1990, Society for Mining, Metallurgy and Exploration, Inc. Doyle, F M editor, 1990.
- Durkin 1990. "Neutralization of Spent Ore from Cyanide Heap Leach Gold Mine Facilities in the Black Hills of South Dakota - Current Practices and Requirements", by Thomas V. Durkin, Hydrologist, South Dakota Department of Water and Natural Resources, Exploration and Mining Program, Pierre, South Dakota, undated, but published in the AIME's Proceedings of the 4th Western Regional Conference on Precious Metals and the Environment, Lead, South Dakota, September, 1990.
- ELI 1992. State Regulation of Mining Waste: Current State of the Art, Environmental Law Institute, November, 1992.
- Engineering Journal 1988. "Tailings Retreatment in Northern Ontario: ERG Resources Starts Up Canada's Highest-Tonnage Gold Operation", Keith R Suttill, International Editor, Engineering and Mining Journal, page 58, September 1988.
- EPA 1984. US Environmental Protection Agency, South Dakota Department of Water and Natural Resources, *Whitewood Creek Study*, Homestake Mining Company, November, 1984.
- EPA 1985. US Environmental Protection Agency, Office of Solid Waste, Report To Congress: Wastes From the Extraction and Beneficiation of Metallic Ores, Phosphate Rock, Asbestos, Overburden From Uranium Mining, and Oil Shale, EPA/530/SW-85-033, Washington, DC, December, 1985.
- EPA 1990. US Environmental Protection Agency. *Superfund Remedial Investigation/Feasibility Study Report, Cimarron Mining Corporation Site*. Washington, DC, June 1990.
- EPA 1991. Mining Waste NPL Site Summary Reports, US Environmental Protection Agency, Final Draft, June 1991.
- EPA 1992a. Mining Industry Profile: Gold, Environmental Protection Agency, Office of Solid Waste, Special Waste Branch, August 1992.
- EPA 1994. Mining Industry Profile: Extraction and Beneficiation of Ores and Minerals - Volume 2: Gold. Environmental Protection Agency, Office of Solid Waste, Special Waste Branch, August 1994.
- EPA 1992b. Predicting Acid Generation from Non-Coal Mining Wastes: Notes of July 1992 Workshop, Draft, prepared by Science Applications International Corporation, for U S Environmental Protection Agency, Office of Research and Development, Environmental Monitoring Systems Laboratory, Las Vegas, Nevada.
- EPA VI 1990. US Environmental Protection Agency, Region VI, *Superfund Remedial Investigation/Feasibility Study Report, Cimarron Mining Corporation Site*, June 15, 1990.
-

- EPA VIII 1989. US Environmental Protection Agency, Region VIII, *Superfund Feasibility Study, Whitewood Creek, South Dakota*. Denver, Colorado, December, 1989.
- EPA VIII 1990. US Environmental Protection Agency, Region VIII, *Superfund Record of Decision for the Whitewood Creek Superfund Site*. Denver, Colorado, March 1990.
- EPA X 1990. US Environmental Protection Agency, Region X, *Remedial Investigation Report, Silver Mountain Mine*, January 19, 1990.
- EPA X 1990. US Environmental Protection Agency, Region X, *Superfund Record of Decision; Silver Mountain Mine Superfund Site*. Seattle, Washington, March 1990.
- Fitzpatrick 1992. Environmental Cost Impact to Gold Mine Development - The Zortman/Landusky Experience, Fitzpatrick, J F, J M Willson, M L Clark, S W Banning, presented at the SME Annual Meeting, Phoenix, Arizona, February 24-27, 1992. SMME Preprint.
- GAO 1991. US General Accounting Office, Report to the Chairman, Subcommittee on Mining and Natural Resources, Committee on Interior and Insular Affairs, House of Representatives, Mineral Resources: Increased Attention Being Given to Cyanide Operations, GAO/RCED-91-145, June 1991.
- Higgs 1992. Technical Guide for the Environmental Management of Cyanide in Mining, British Columbia Technical and Research Committee on Reclamation, Cyanide Sub-Committee, prepared by T W Higgs Associates Ltd in association with EVS Consultants Ltd, ASL Laboratories Ltd, and Gormely Process Engineering, July 1992.
- Idaho Title 1 1992. Idaho Title 1, Chapter 13: Rules and Regulations for Ore Processing By Cyanidation, January 6, 1988, revised April 23, 1992. (Sections 01.13000 to 01.13999)
- Idaho 1993. Personal communication between Jerry Yoder, Idaho Division of Environmental Quality, Water Quality Bureau, and Michelle Stowers, Science Applications International Corporation, on May 11, 1993.
- INCO 1992. INCO undated presentation notes. Included in materials sent to Susan McCarter, Science Applications International Corporation, by INCO, October 15, 1992.
- Ingles and Scott 1987. State of the Art of Processes for the Treatment of Gold Mill Effluents, Ingles, J, and J S Scott, Environment Canada, Mining and Milling Section, March 1987.
- Joy 1990. Personal communication between J Joy, South Carolina Department of Health and Environmental Control, and Joe Rissing, Science Applications International Corporation, on January 14, 1990.
- Kiel 1988. Introduction to Evaluation, Design and Operation of Precious Metals Heap Leach Projects, Kiel, J, D van Zyl, and J R Dorey editors. Society of Mining Engineers, 1988.
- Konigsmann et al. 1989. Water Management and Effluent Treatment Practice, Golden Giant Mine, Hemlo Gold Mines, Inc. Eric Konigsmann, Ernest Goodwin, and Chris Larsen, for presentation at the Canadian Mineral Processors Conference, January 17, 1989.

- Landusky/Montana 1993a. State of Montana, Department of State Lands, letter to James Geyer, Zortman Mining Inc., re: review of reclamation plans and monitoring, February 16, 1993.
- Landusky/Montana 1993b. Zortman Mining Inc., letter to Sandra Olsen, Department of State Lands, Hardrock Bureau, re: attainment schedule for reclamation activities, March 15, 1993.
- Lien 1991. "Biological and Chemical Cyanide Destruction from Heap Leachates and Residues", Lien, R H, B E Deinslate, and P B Altringer, February, 1991. See Lootens, D J, et al. editors.
- Lien and Altringer 1993. Case Study: Bacterial Cyanide Detoxification During Closure of the Green Springs Gold Heap Leach Operation, R H Lien and P B Altringer, US Bureau of Mines, Prepublication of paper to be presented at the International Biohydrometallurgy Symposium, Jackson Hole, Wyoming, August 22-25, 1993. Also presented at Mine Operations and Closure Short Course, Helena, Montana, April 27-29, 1993.
- Logue Undated. Nancy Logue, Pegasus Gold Corporation, Updating Pegasus Gold's Relief Canyon Mine Reclamation Plan - 1984 Versus 1990 Standards, pages 105 to 109, undated document.
- Lopes and Johnston 1988. "A Technical Review of Heap Leaching", Lopes, R.F., and R.J. Johnston, In *Environmental Management for the 1990s*, proceedings of the Symposium on Environmental Management for the 1990s, Denver, Colorado, February 25-28, 1991, D J Lootens, W M Greenslade, and J M Barker (editors). Society for Mining, Metallurgy, and Exploration, Inc., August 1988.
- Lootens 1991. Environmental Management for the 1990's, proceedings of the Symposium on Environmental Management for the 1990's, Denver, CO. February 25-28, 1991. Littleton, CO: Society for Mining, Metallurgy, and Exploration, Inc., Lootens, D J, W M Greenslade, and J M Barker editors, February, 1991.
- McGill and Comba 1990. A Review of Existing Cyanide Destruction Practices, McGill, Sandra L, and Paul G Comba, U.S. Bureau of Mines, Reno Research Center, Presented at the Nevada Mining Association, Nevada Department of Wildlife, Wildlife/Mining Workshop, Reno, Nevada, March 29, 1990.
- Miereau 1991. Personal communication between D Miereau, Nevada Department of Conservation and Natural Resources, Environmental Protection Division, Bureau of Mines and Reclamation, and W Keeton, Science Applications International Corporation on February 26, 1991.
- Minerals Today 1993. "Hecla's Yellow Pine Unit Closes, Exploration Continues", Minerals Today, page 31, February 1993.
- Mining Engineering 1992. "Start-up and operation of Placer Dome's Campbell Mine gold pressure oxidation plant," John Frostiak and Bret Haugrud, Mining Engineering, Volume 44, No 8, page 991, August, 1992.
- Mining Journal 1990. "Cyanide and the Environment", Jim V Rouse, Director of Geohydrology, Mining Journal, page 18, August 24, 1990.
- Mohr Undated. Operational and Final Reclamation Activities at the Thunder Mountain Mine, Rick Mohr, Coeur d'Alene Mines Corporation, undated.

- Mudder and Smith 1992. Solution Management During Decommissioning of Heap Leach Operations, T I Mudder and A Smith, paper presented at Society for Mining, Metallurgy, and Exploration's Annual Meeting, Phoenix, Arizona, February 24-27, 1992. SMME Preprint.
- Mudder and Whitlock 1984. "Biological Treatment of Cyanidation Waste Waters", Mudder, T I, and J L Whitlock, In *Mineral and Metallurgical Processing*, Society for Mining, Metallurgy, and Exploration, Inc., August, 1984.
- National Park Service 1986. US Department of the Interior, National Park Service, Energy, Mining, and Minerals Division, Environmental Handbook for Cyanide Leaching Projects, June 1986. Prepared by Michael D Stanton, Thomas A Colbert, & Richard B Trenholme of Intermountain Soils, Inc., Denver, CO, under contract to Radian Corporation for the National Park Service.
- Nevada Undated. Nevada Regulations governing Design, Construction, Operations and Closure of Mining Operations, NAV Sections 445.242 to 445.24388.
- Nevada 1990. Nevada Department of Conservation and Natural Resources, Division of Environmental Protection, "Evaluations for Closure," October 29, 1990.
- Nevada 1993a. Personal communication between Doug Zimmerman, Nevada DEQ, and Joe Rissing, Science Applications International Corporation, on January 11, 1993.
- Nevada 1993b. Personal communication between Glen Miller, University of Nevada - Reno, and Joe Rissing, Science Applications International Corporation, on January 13, 1993.
- Nevada 1993c. Personal communication between Kathy Sertic, Nevada Bureau of Water Quality Planning and Joe Rissing, Science Applications International Corporation, on January 21, 1993.
- Nevada 1993d. State of Nevada, Department of Conservation and Natural Resources, Division of Environmental Protection (DEP), re: closure activities for Ren Gold Mine, package of information sent to Joe Rissing, Science Applications International Corporation, February 16, 1993.
- Noranda 1994. Personal communication between Chris R. Larsen, Noranda Technology Center, and Michelle Sonnenfeldt, Science Applications International Corporation, on August 31, 1994.
- ORD 1993. Personal communication between Ed Heithmar, U.S. EPA Office of Research and Development, and Michelle Stowers, Science Applications International Corporation, on May 20, 1993.
- Pay Dirt. 1992. Rocky Mountain, September 1992, pg. 10A.
- Ritcey 1989. Tailings Management, Problems and Solutions in the Mining Industry, Process Metallurgy 6, Gordon M Ritcey, 1989.
- RM2 1991. RM2 Briefing on Cyanidation Mining, November 22, 1991. With cover memo 11/21/91 from EPA, Linda Vlier Moos, re: Cyanidation Mining Paper.
- RWQCB 1987. California Regional Water Quality Control Board "Cyanidation Requirements for Cyanidation Process Wastes", Internal Memorandum, from Dr Ranjit S Gill, E.S. IV, to O R Butterfield, Executive Officer, April 22, 1987.

- Salomans & Forstner 1988. Environmental Management of Solid Waste, Dredged Materials and Mine Tailings, W Salomans, U Forstner, Editors, 1988.
- Schafer and Associates 1990. Cyanide Degradation and Decommissioning of Spent Heap-Leach Ore at the Landusky Mine, prepared by Schafer and Associates, in association with EIC, Inc., December 28, 1990.
- Schafer and Associates 1991a. Cyanide Degradation and Rinsing Behavior in Landusky Heaps, Final Report, prepared for Zortman Mining Inc. by Schafer and Associates in association with EIC Corporation, January 22, 1991.
- Schafer and Associates 1991b. Engineering and Environmental Aspects of Mine Waste Disposal, Short Course, 1991 SME Annual Meeting, February 22-24, Denver, Colorado. With Case History: Cyanide Degradation and Rinsing of Spent Ore Heap Leach Gold Facilities, by William M. Schafer, Schafer and Associates, Bozeman, Montana (based on the Zortman-Landusky Mine in Montana).
- Smith & Mudder 1991. Chemistry and Treatment of Cyanidation Wastes, Adrian Smith and Terry Mudder, Mining Journal Books Limited, London, 1991.
- South Carolina 1980. *Mining Act Rules and Regulations, Chapter 89*, South Carolina Code of Regulations, 1980.
- South Carolina 1993a. Personal communication between Craig Kennedy, South Carolina Department of Land Resources, and Joe Rissing, Science Applications International Corporation, on January 13, 1993.
- South Carolina 1993b. Personal communications between Birgit McDade, South Carolina Department of Health and Environmental Control, and Joe Rissing, Science Applications International Corporation, on January 13, 1993.
- South Dakota 1993. Personal communication between Tom Durkin, South Dakota Office of Minerals and Mining, and Joe Rissing, Science Applications International Corporation, on January 19, 1993.
- Stanford 1987. "Amax Sleeper Mine Exceeds Expectations On All Counts As Low-Cost Gold Producers." W D Stanford, Mining Engineering: 241-46, April, 1987.
- Thompson and Gerteis 1990. New Technologies for Mining Waste Management: Biotreatment Processes for Cyanide, Nitrates and Heavy Metals, L C Thompson and R L Gerteis, Gold Fields Mining Corporation, presented at the Western Regional Symposium on Mining and Mineral Processing Wastes, May 30-June 1, 1990, University of California at Berkeley, published in Mining and Mineral Processing Wastes, Fiona M Doyle, editor, SMME Publishers, Littleton, Colorado, 1990. Also in course notes for Mine Operations and Closure, Short Course, Helena Montana, April 27-29, 1993.
- Todd 1986. Cyanide Degradation Study, Gold Fields Operating Company - Mesquite, Larry Todd, Plant General Foreman, July 1986.
- US DOI 1992. US Department of Interior, Bureau of Mines, Gold Annual Report for 1991. Written by John M. Lucas, December 1992.
- USFS 1993. Personal communication between US Forest Service, Minerals Branch and Michelle Stowers, Science Applications International Corporation on May 10, 1993.

- Van Zyl 1988. Introduction to Evaluation, Design, and Operation of Precious Metal Heap Leaching Projects, Society for Mining, Metallurgy, and Exploration, Inc., D J A van Zyl, I P G Hutchinson, and J E Kiel, editors, 1988.
- Vergunst 1991. Heap Pad Detoxification at Snow Caps Mine Using the INCO Process, R D Vergunst, P F Iamarino, B Tandi, E A Devuyst, Inco Exploration and Technical Services, paper presented at the 30th Annual Conference of Metallurgists, CIM, Ottawa, Canada, August 18-21, 1991.
- Vick 1990. Planning, Design, and Analysis of Tailings Dams, Steven G Vick, BiTech Publishers Ltd., Vancouver, B C Canada, 1990.
- Volpe & Kelly 1985. Seepage and Leakage from Dams and Impoundments, American Society of Civil Engineers, edited by Richard L Volpe and William E Kelly, May 5, 1985.
- Washington DOE. Washington Department of Ecology, *Potential Hazardous Wastes Site: Preliminary Assessment, Silver Mountain Mine, Washington*, undated.
- Weiss 1985. *SME Mineral Processing Handbook*, Society of Mining Engineers, Weiss, N L editor, 1985.
- WGA 1991a. Western Governor's Association, Mine Waste Task Force, *Regulatory Issues in Cyanide Processing - A Hands-On Conference for State Regulatory Officials*, March 1991.
- WGA 1991b. Western Governor's Association, Mine Waste Task Force, *Abstracts of Precious Metal Mining and Water Quality Permitting Procedures*, Special project by South Carolina, Draft 1991.